Standard Model Tests with Top Quarks

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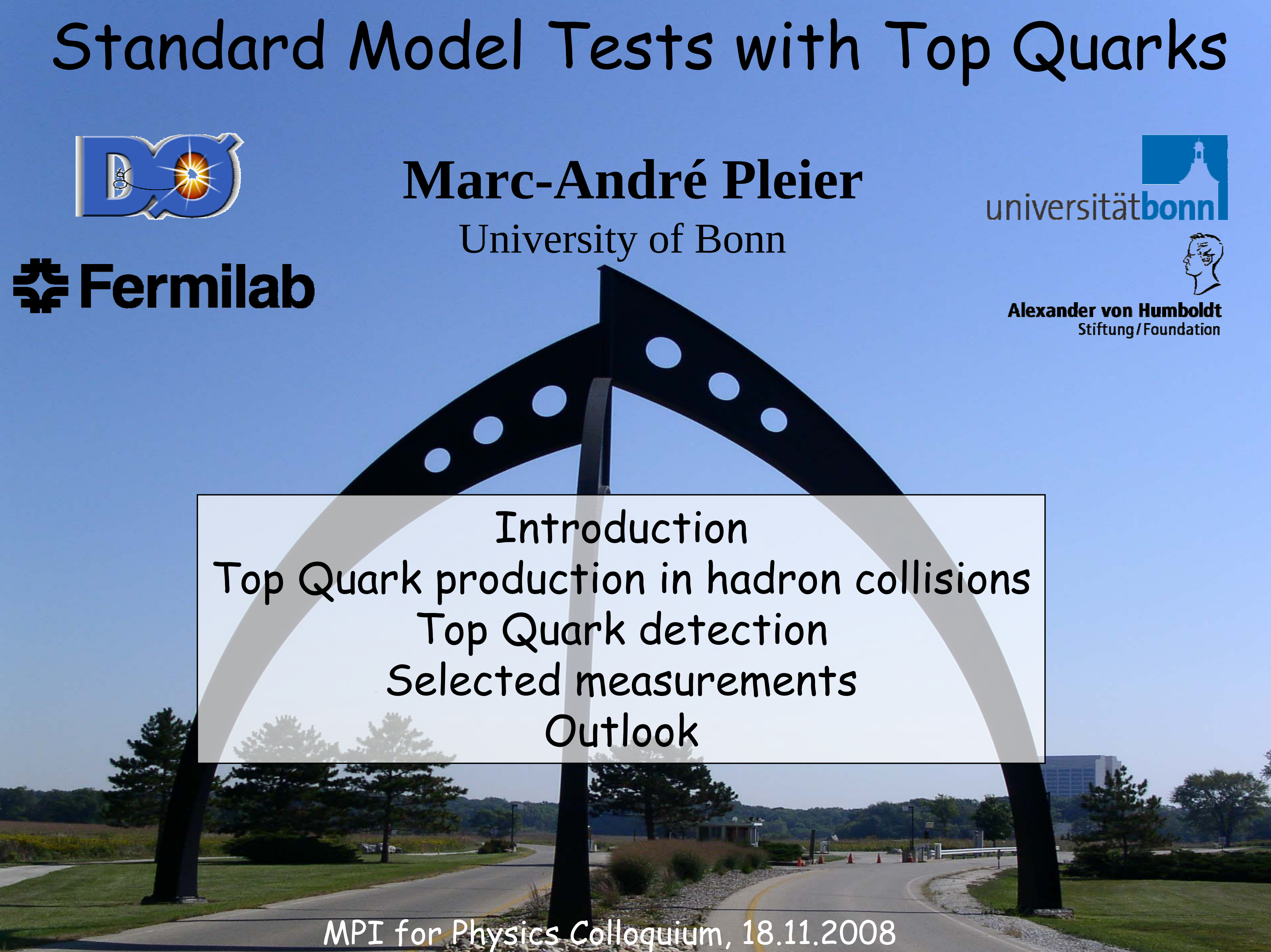
Introduction

Top Quark production in hadron collisions

Top Quark detection

Selected measurements

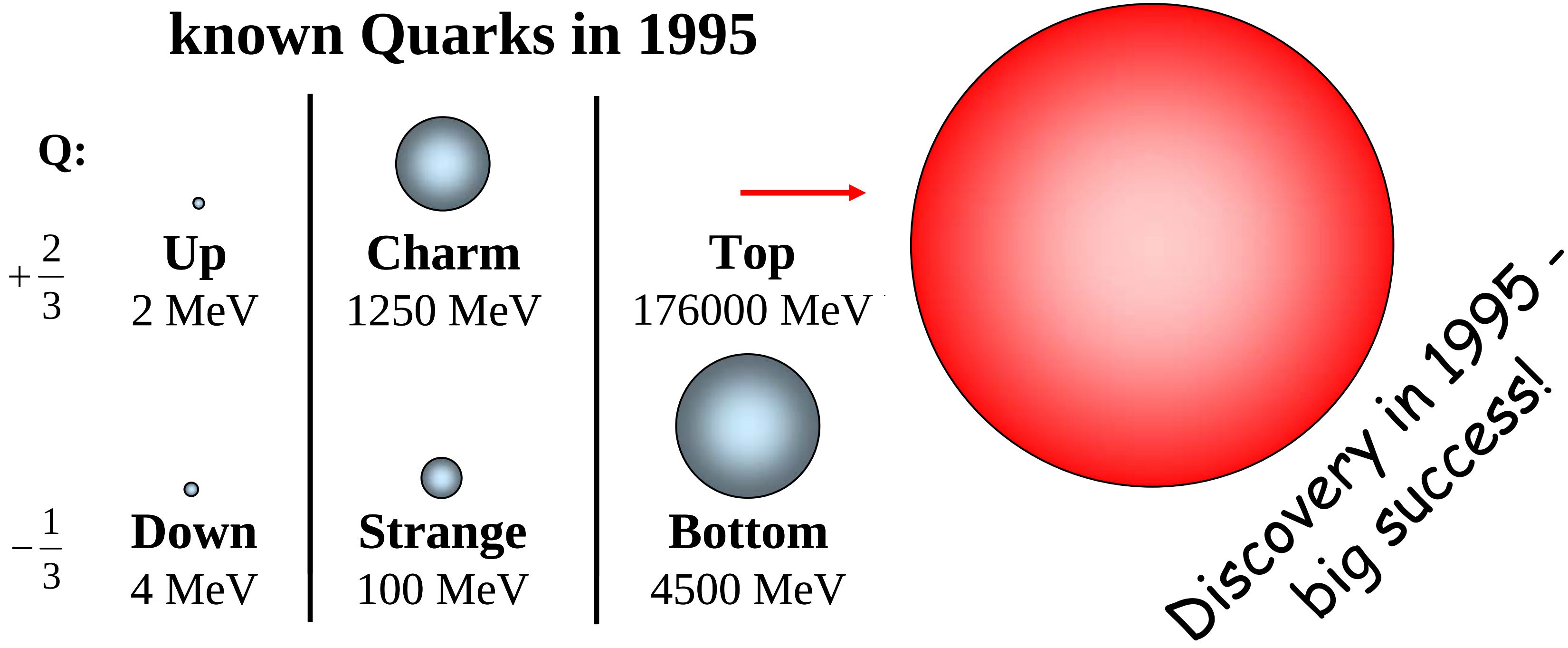
Outlook



MPI for Physics Colloquium, 18.11.2008

The discovery of the Top Quark

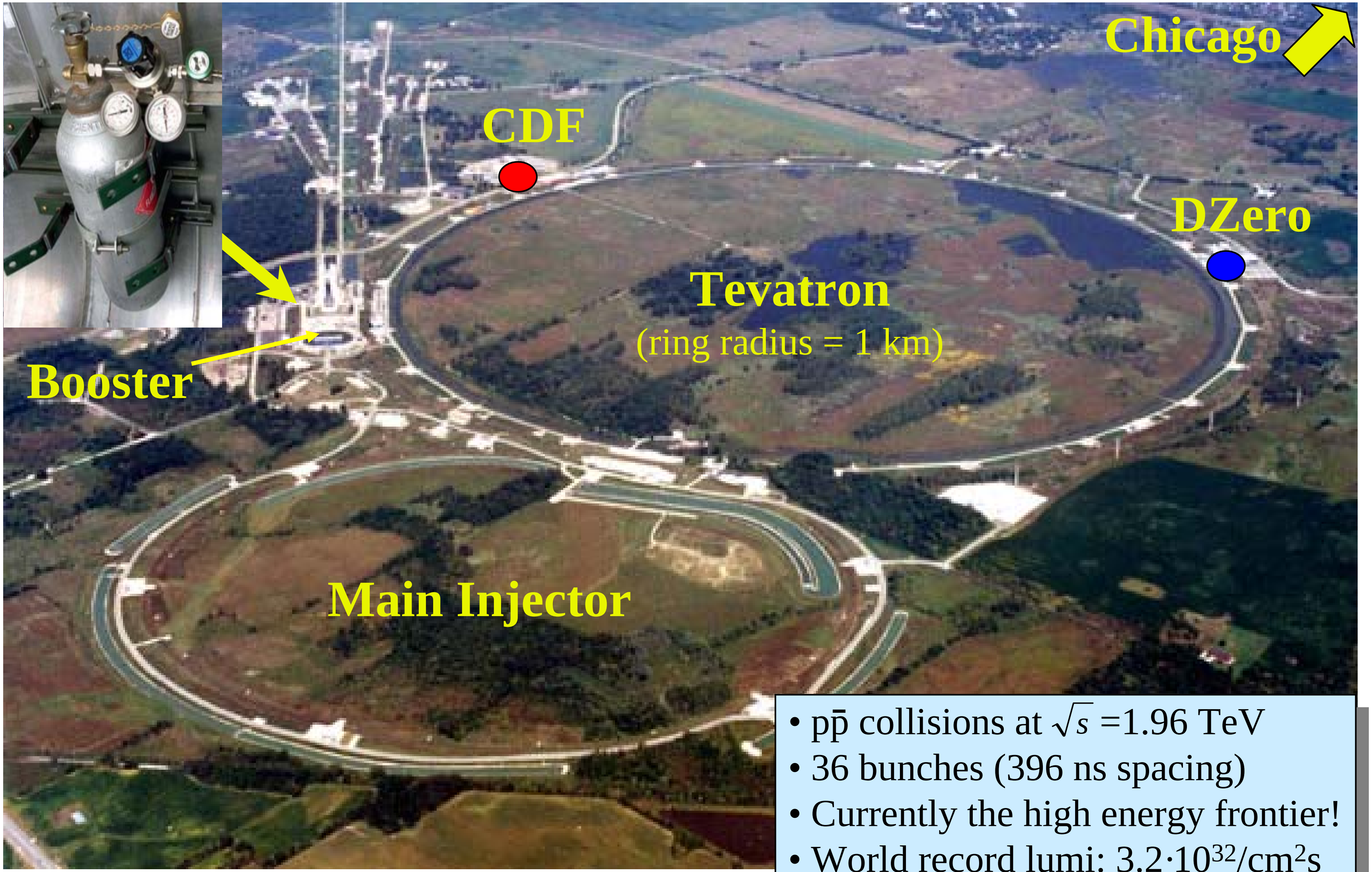
known Quarks in 1995



- **Top is massive: $m_t = 176 \pm 13$ GeV**
- **Short lifetime $\tau \approx 5 \cdot 10^{-25}$s => no hadron formation!**
- **Is this really the Standard Model Top Quark???**

Where can we study Top Quarks?

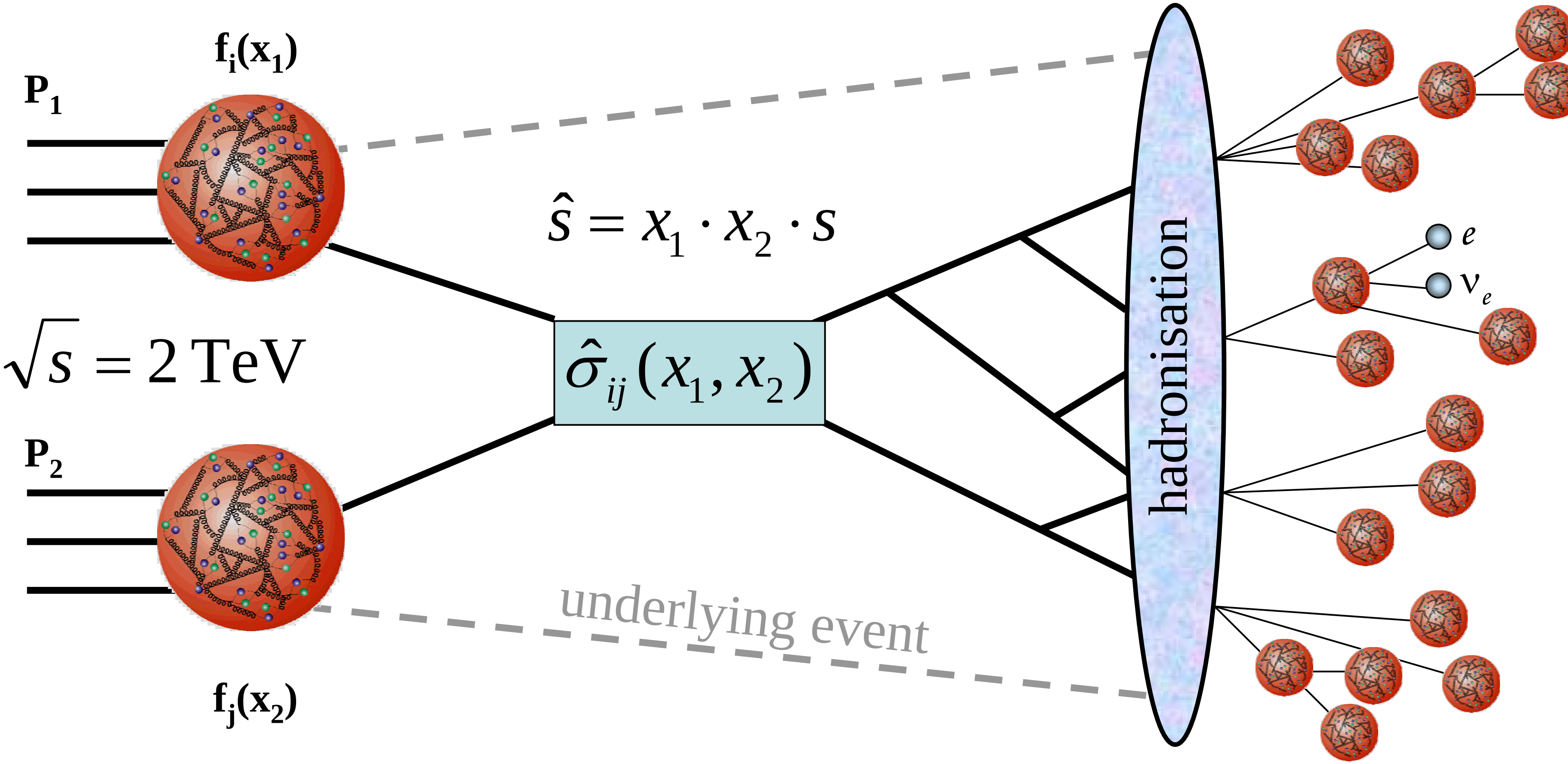
The Tevatron @ Fermilab



- $p\bar{p}$ collisions at $\sqrt{s}$ =1.96 TeV
- 36 bunches (396 ns spacing)
- Currently the high energy frontier!
- World record lumi: $3.2 \cdot 10^{32}/cm^2s$

The experimental challenge

Highest energies are reached by hadron colliders. BUT: collision of composite particles!



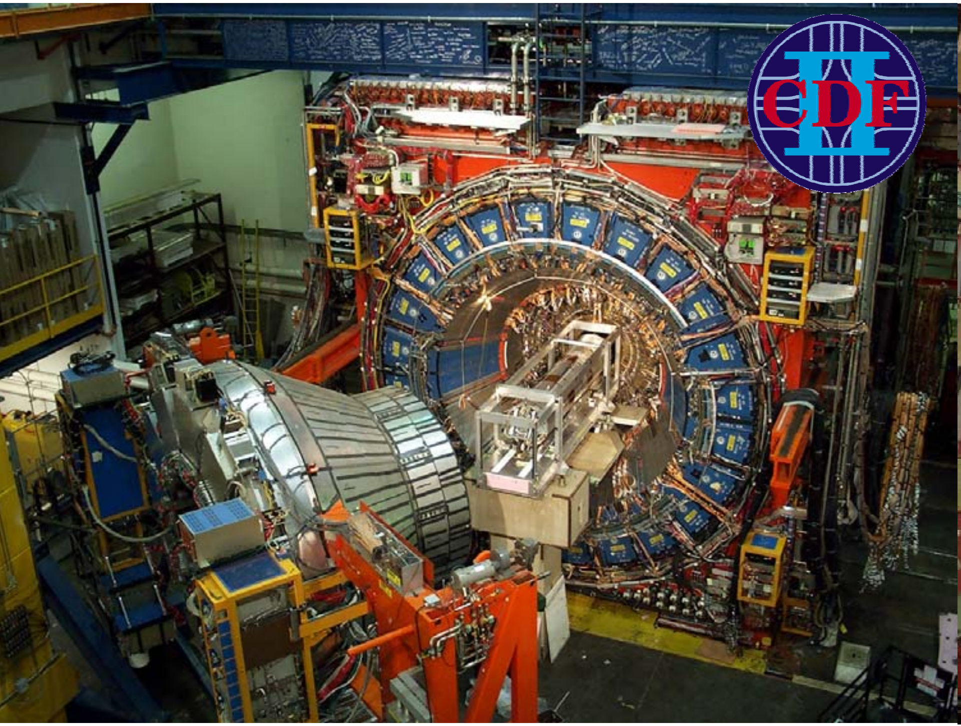
non-perturbative universal parton distribution functions (PDFs)

hard interaction

particle "jets"

The Tevatron Collider Experiments

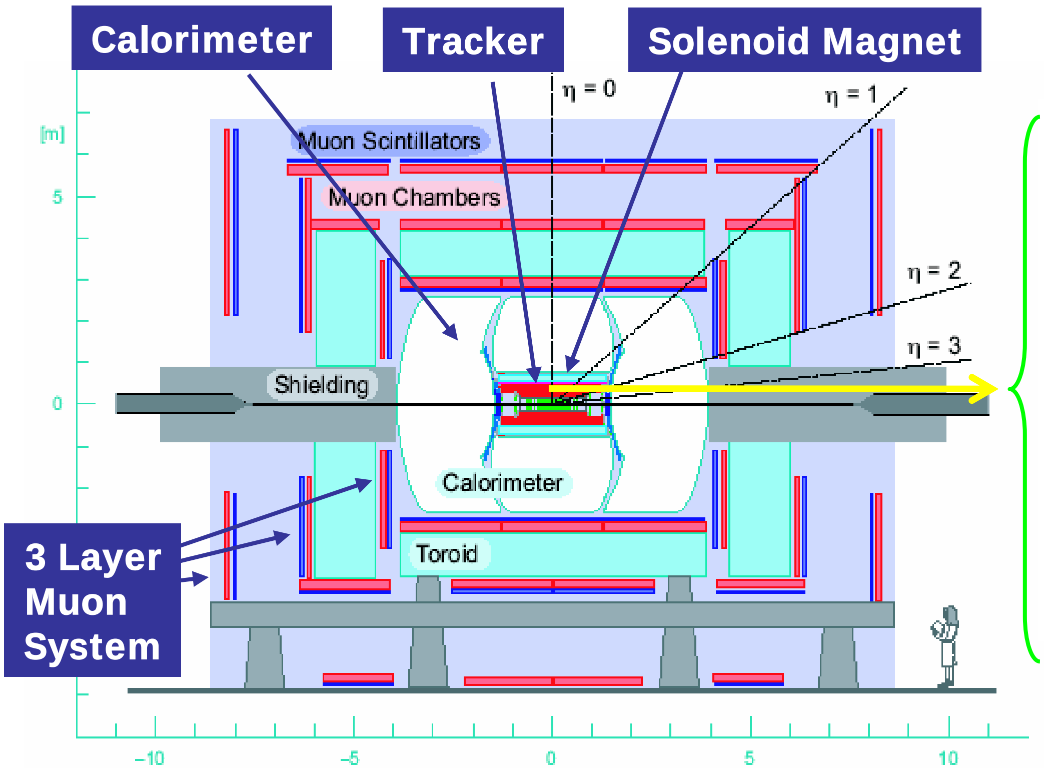
Multi-purpose collider detectors:

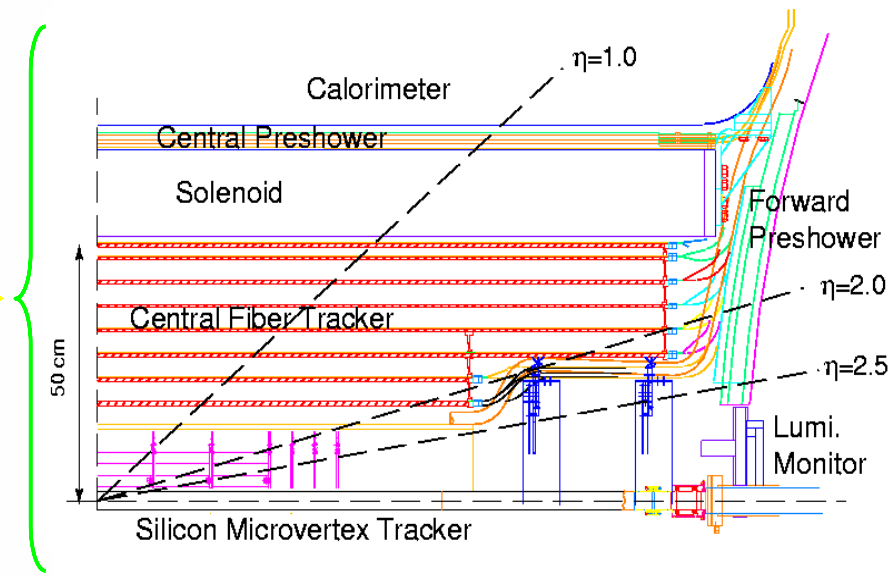


- 14 countries,
- 59 institutions,
- ~600 physicists

- 18 countries,
- 82 institutions,
- ~550 physicists

The DZero Detector





- Excellent calorimetry

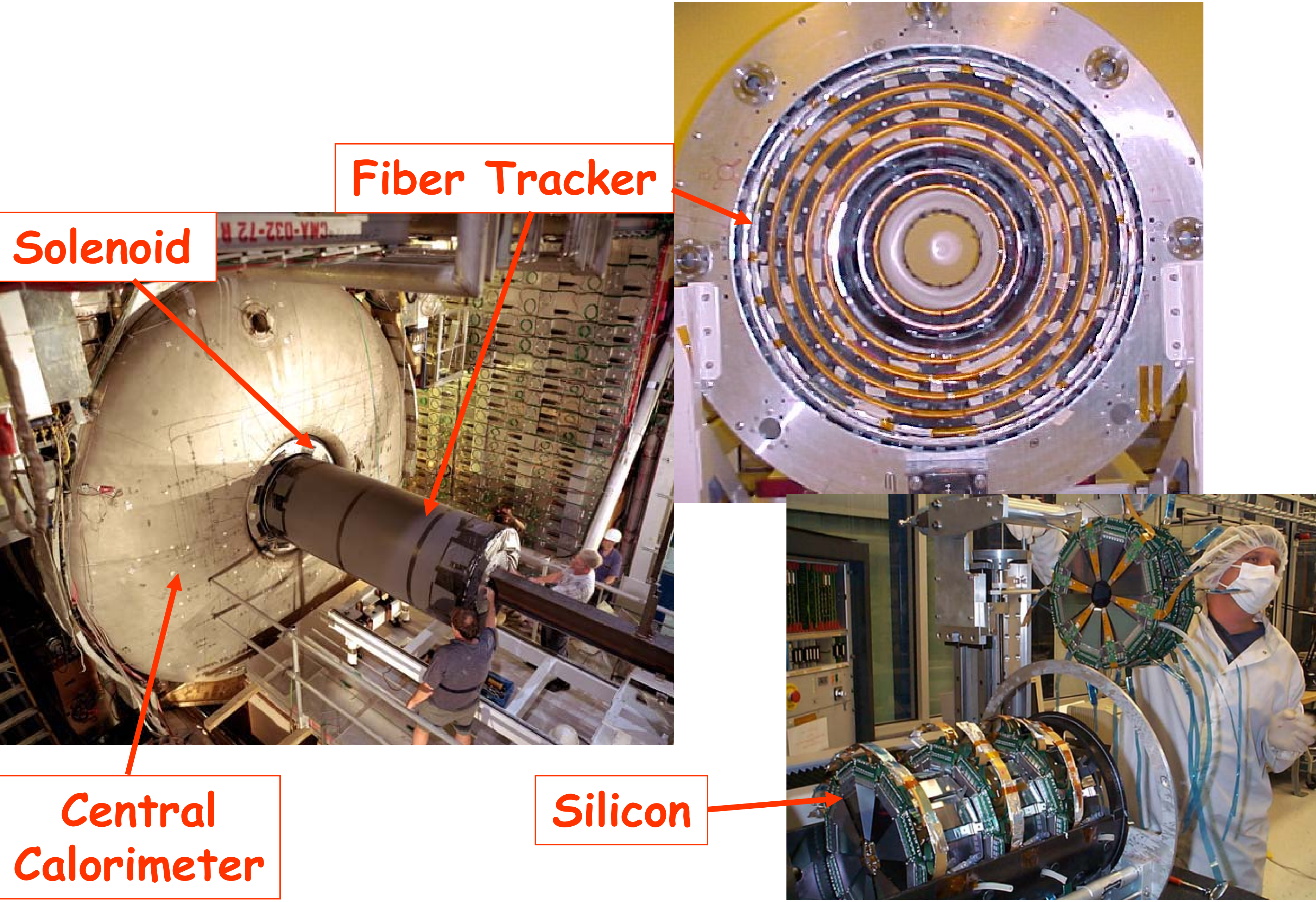
$$\frac{\sigma_E}{E} = \frac{15\%}{\sqrt{E}} \oplus 0.3\% \text{ (elm)}, \frac{\sigma_E}{E} = \frac{45\%}{\sqrt{E}} \oplus 4\% \text{ (had)}$$

- Large muon acceptance

- Central tracking inside 2 T solenoid
  - –Silicon vertex detector (=>b-jet ID)
  - –Scintillating fiber tracker

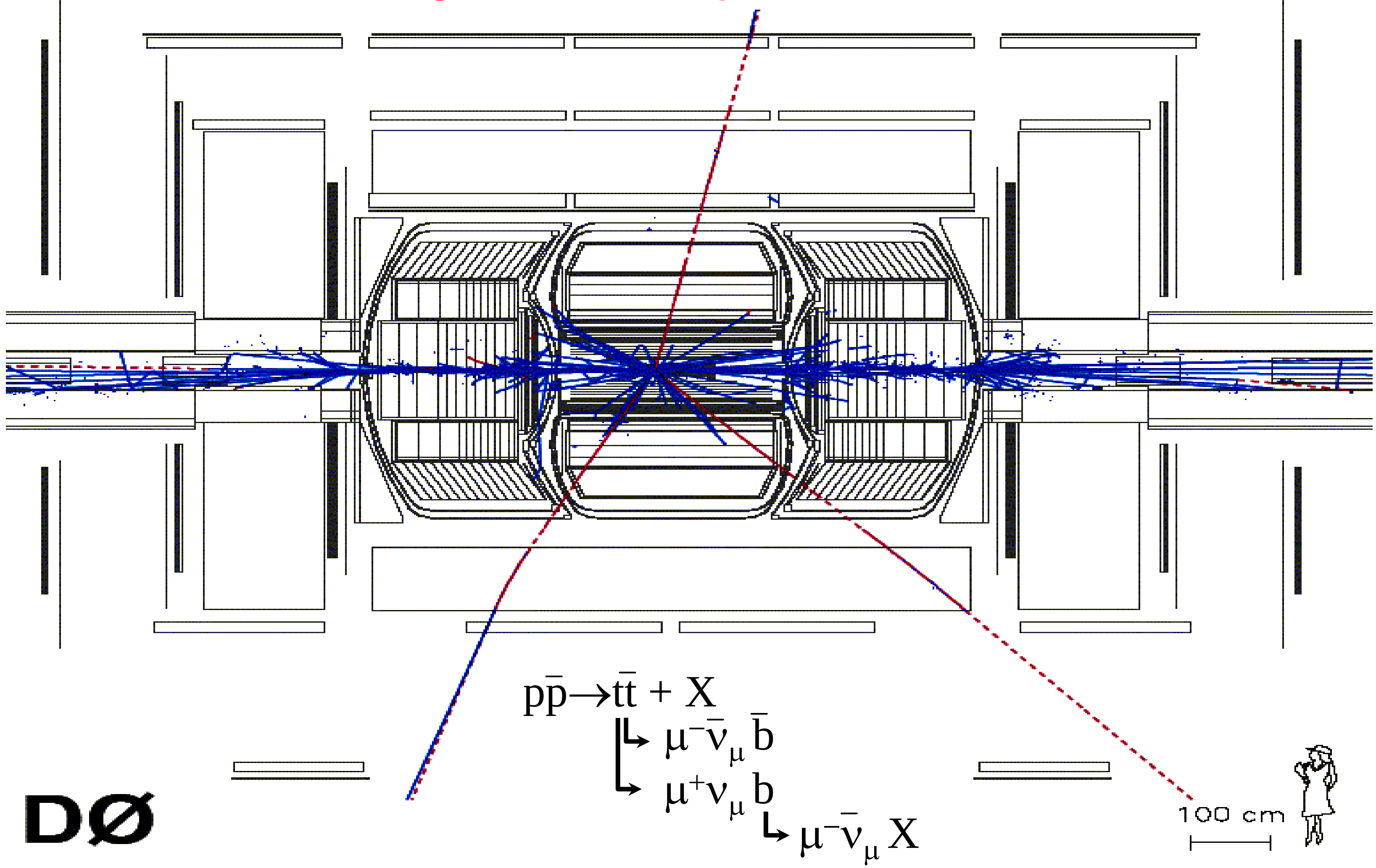
~10 m

~20 m


Fiber Tracker
Solenoid
Central Calorimeter
Silicon

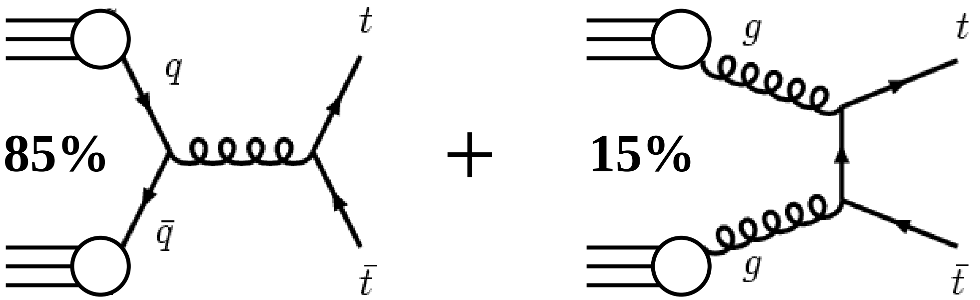
A Top event in the DZero detector

One signal event every 10^{10} interactions



Top Quark Production & Decay

- Main **production** of Top Quarks – via strong interaction in *pairs*:

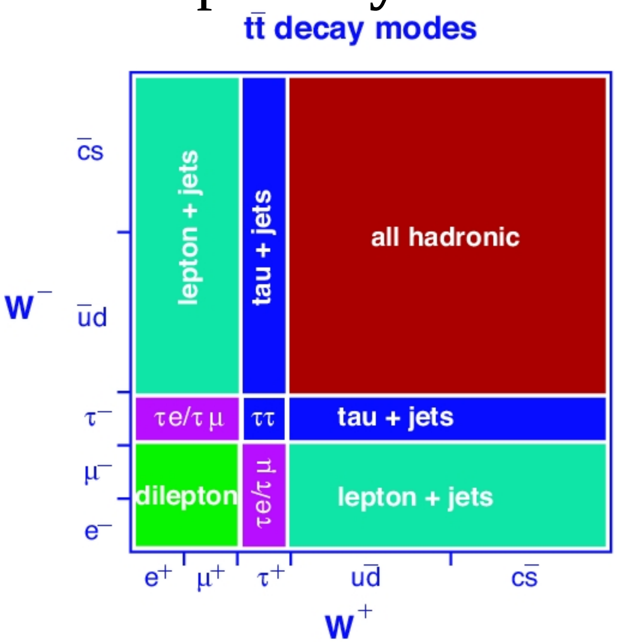


<u>Theoretical expectation:</u>

$$\sigma_{t\bar{t}} = (6.6^{+0.7}_{-0.8})\ \text{pb}$$

Cacciari et al., JHEP0809, 127, m_t=175 GeV

- SM Top **decay** ≈100% Wb ⇒ Final states determined by W decay mode



⇒ 2 b-jets

⇒ Up to two charged leptons/neutrinos

⇒ Up to four additional jets

<u>Need to reconstruct/identify:</u>

- **Electrons, muons, taus**
- **Missing transverse energy,**
- **Jets/b-jets**

Important Measurements

•**Production rate:**

Test Standard Model (QCD) predictions

•**Branching fractions:**

$t \to Wb \,/\, t \to Wq \;\approx 1$?

•**W-helicity:**

Test V-A structure of weak interaction

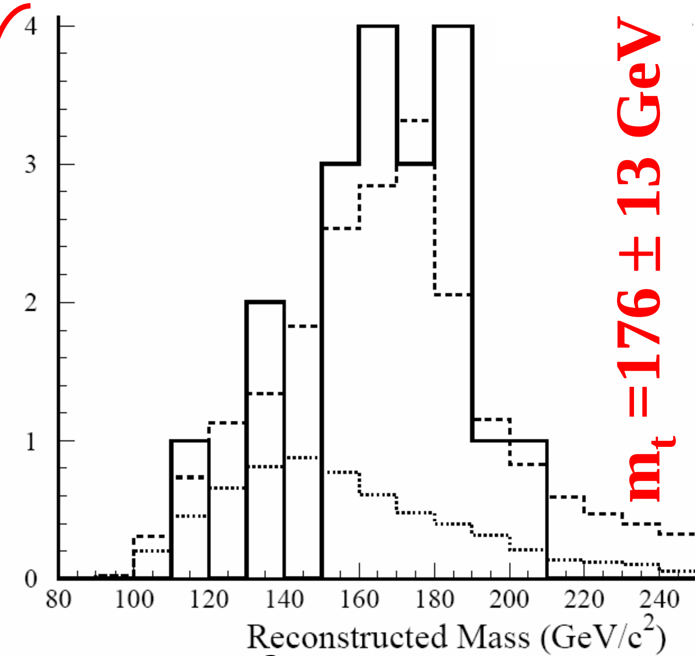
•**Mass:**

Radiative corrections on the W mass allow constraints on **Higgs mass** from m_W, m_t

•**Coupling:**

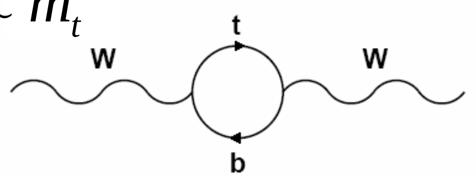
•How strongly does the Top couple to the W boson?

•Are there indications for a fourth generation?

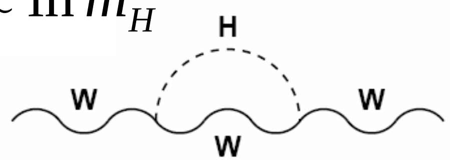


$m_t = 176 \pm 13$ GeV

$$\Delta m_W \propto m_t^2$$



$$\Delta m_W \propto \ln m_H^2$$



Is this the Standard Model Top Quark?

Discovery had 12 Top-events…

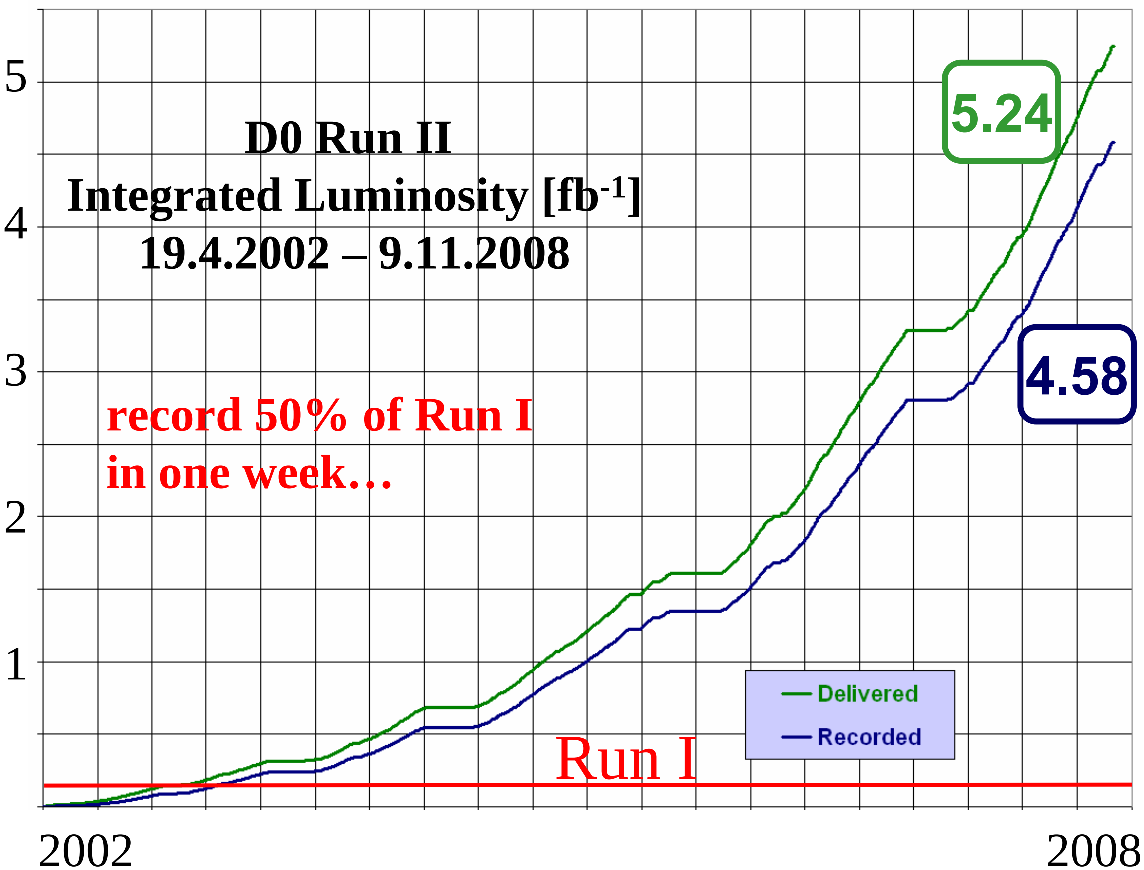
Need precise measurements!

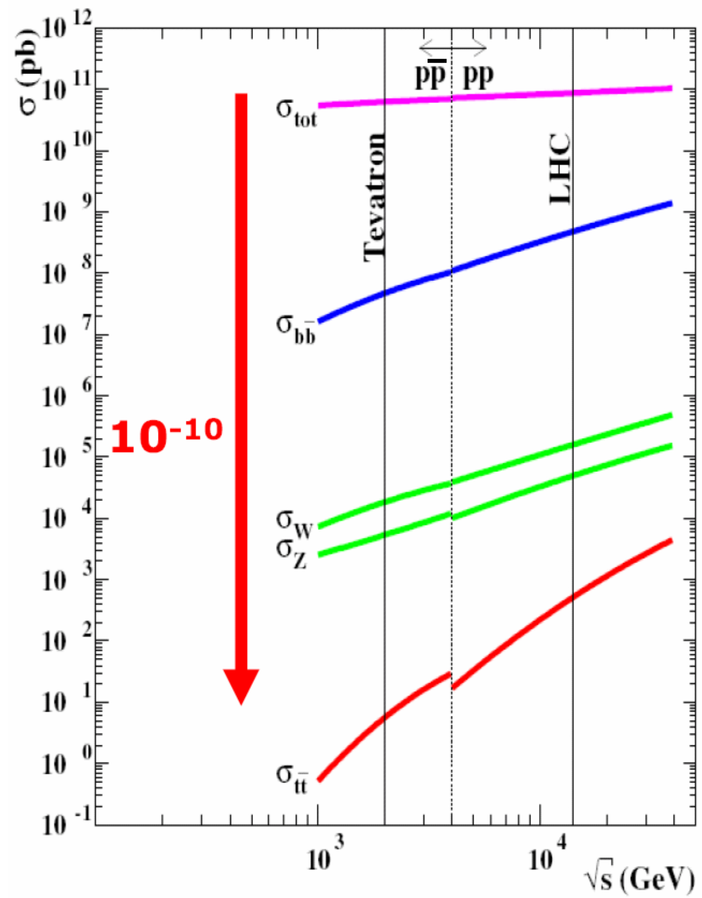
⇒ Need more events!

Top Quark Production @ Tevatron: The precision era

Top Discovery: Tevatron "Run I" ('92-'96): ~125pb^{-1}, $\sqrt{s}$ = 1.8 TeV.

Now "RunII":
- Increased luminosity
- Increased $\sqrt{s}$: 1.96 TeV ⇒ +30% σ_{Top}





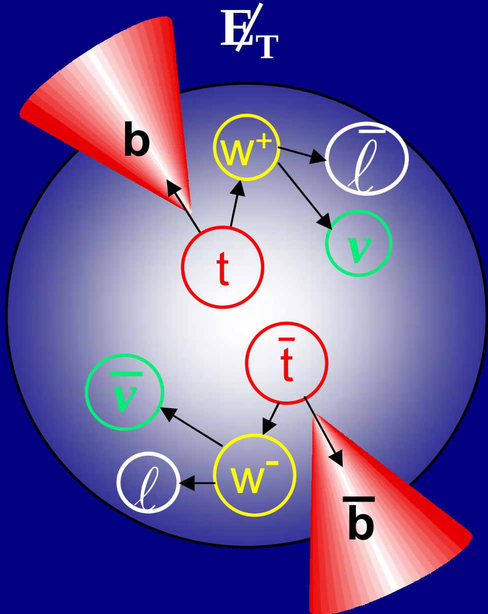
Classification of Top Quark pair events

Dilepton: 10%

Two high-p_T jets

Two high-p_T leptons

$\not{E}_T$

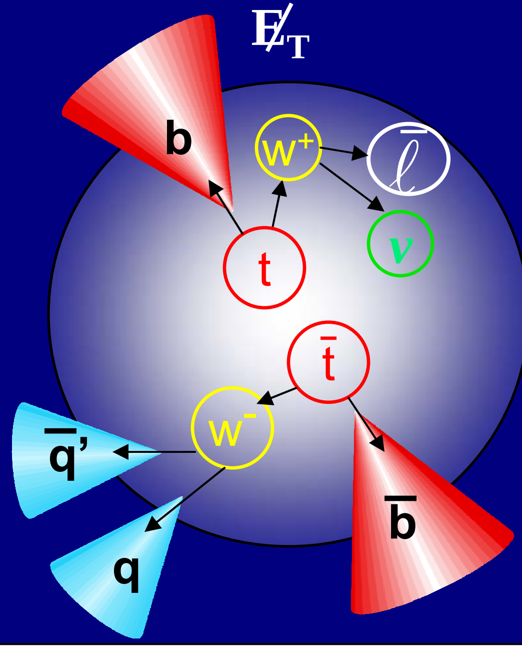


Lepton + Jets: 44%

Four high-p_T jets

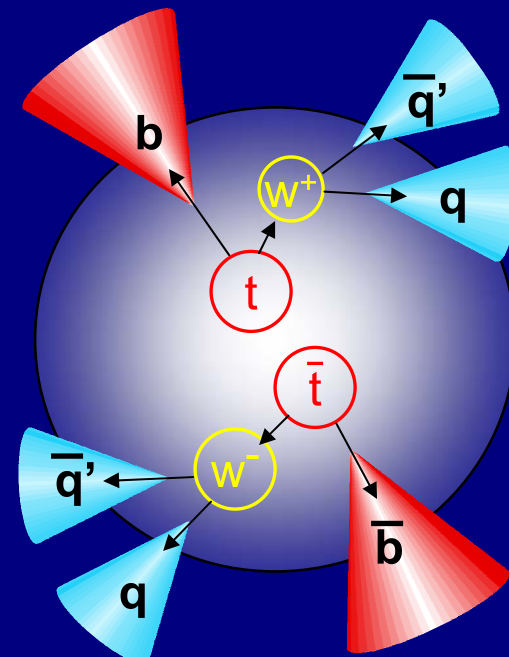
One high-p_T lepton

$\not{E}_T$



All Hadronic: 46%

Six high-p_T jets



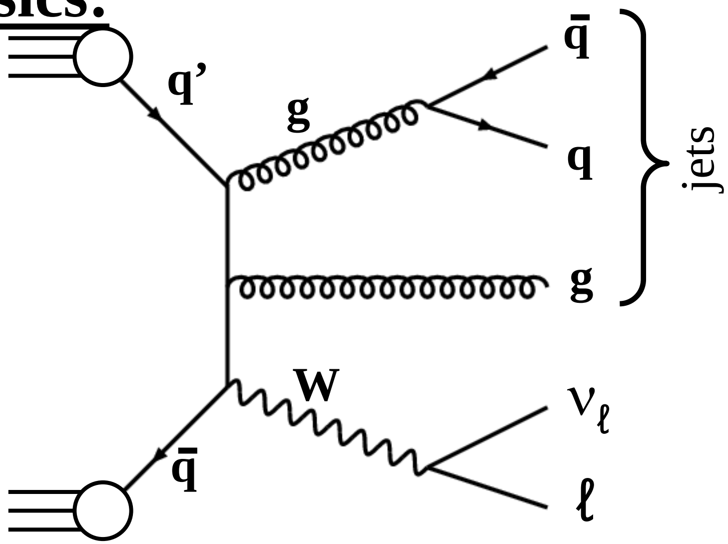
- low branching fraction
- low background
  (WW+jets, Z+jets, W+jets)

- high branching fraction
- manageable background
  (W+jets, "QCD" multijet prod.)

- high branching fraction
- high background
  ("QCD" multijet production)

Main backgrounds

physics:

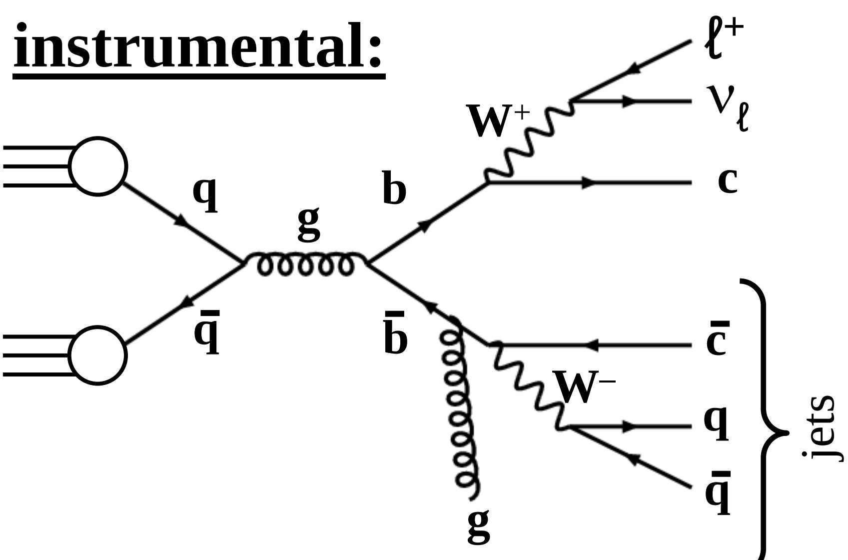


Electroweak W production:

- $W \to \ell+\nu_\ell$
- additional ≥ 3 jets from gluon radiation

→ **use Monte Carlo simulation**

instrumental:

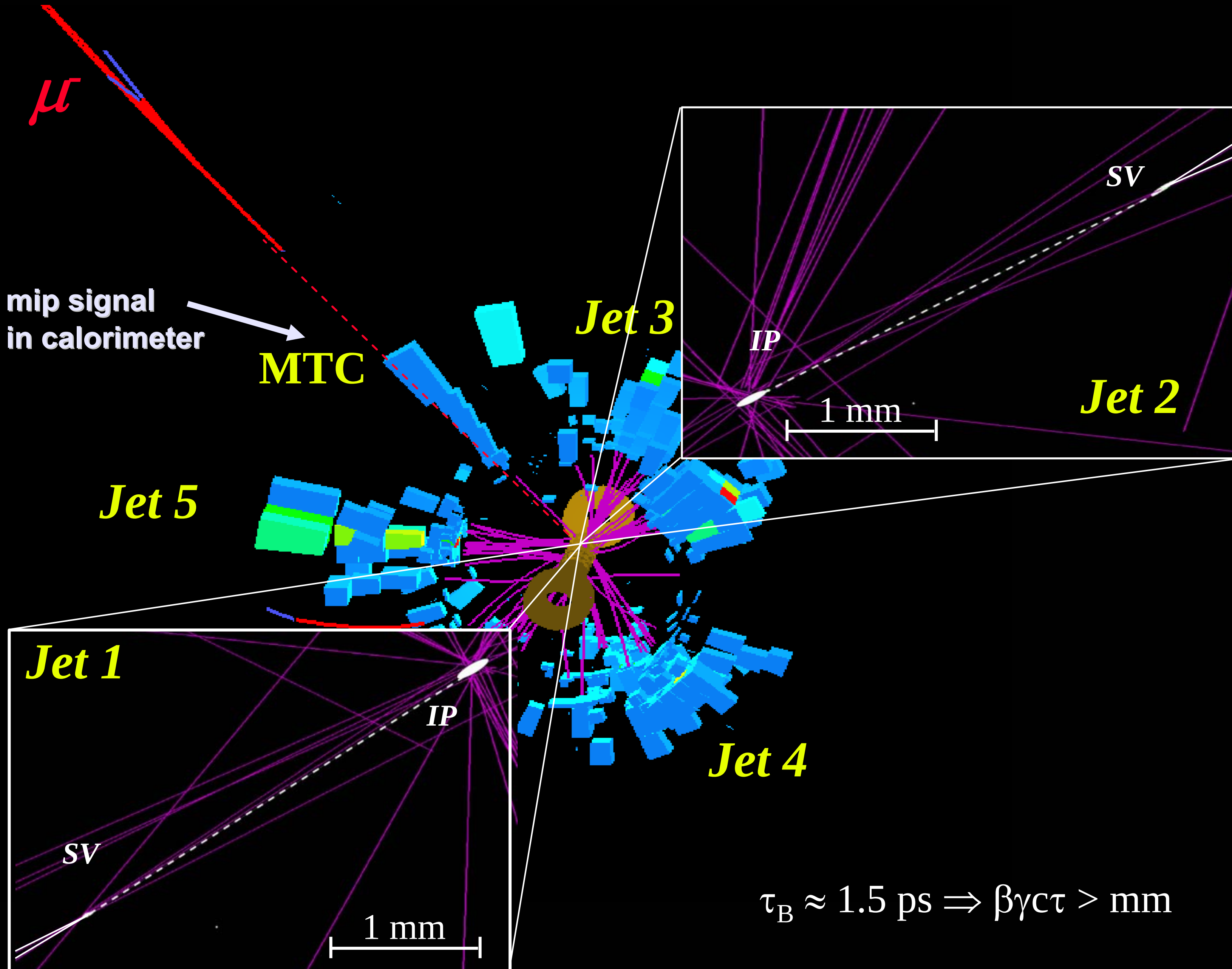


Multijet production with fake lepton, MET:

- Electrons faked by (electromagnetic) jets
- Muon-fakes: real muons, fakely isolated (eg. from semileptonic b-decays, with non-reconstructed b-jet)
- misreconstructed MET

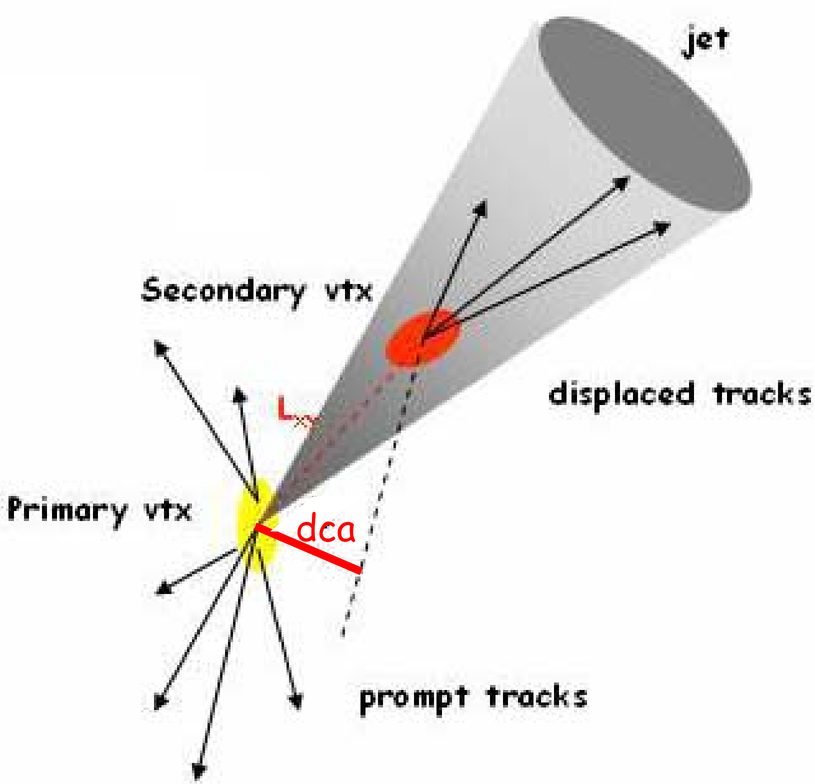
→ **use data to model properly**

$t\bar{t} \rightarrow \mu$+jets candidate event



$\tau_B \approx 1.5$ ps $\Rightarrow \beta\gamma c\tau >$ mm

Lifetime b-tagging at DØ

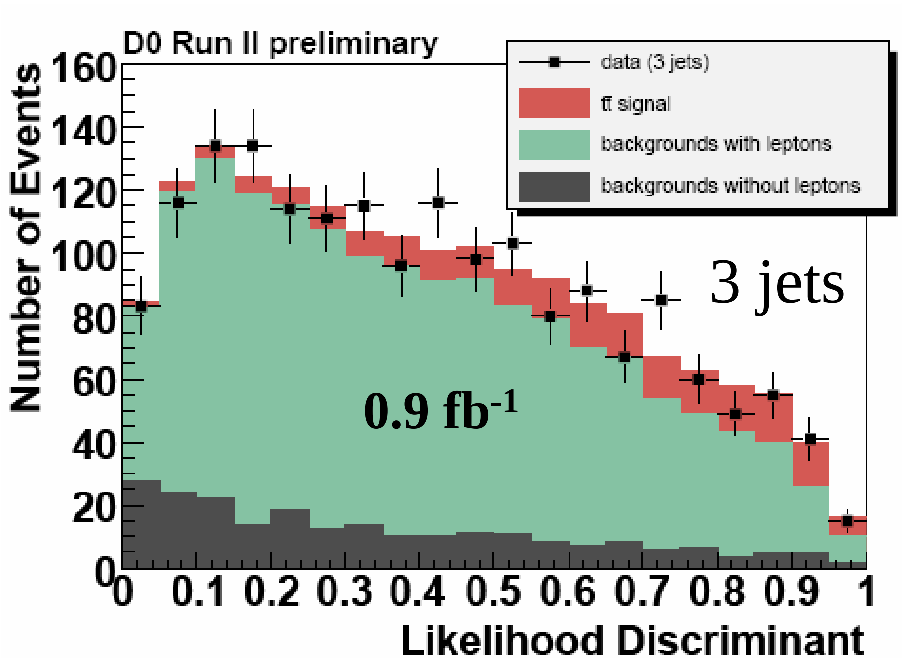


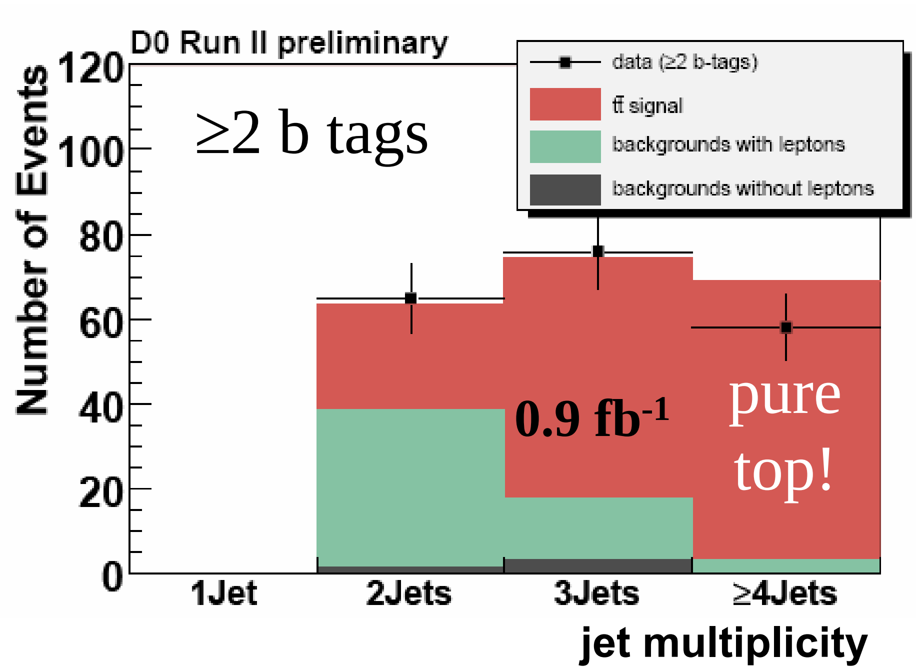
(dca = distance of closest approach)

- Separate *b*-jets from light-quark and gluon jets ⇒ reject most multijet & *W*+jets background processes
- $\tau_B \approx 1.5$ ps ⇒ $\beta\gamma c\tau >$ mm
- Neural network based on impact parameter and reconstructed vertex information
- "Tagging" efficiencies:
  - *b*-jet ≈ 50%
  - *c*-jet ≈ 10%
  - light-jet ≈ 0.5%

Top Quark Pair Production: Lepton+Jets channels

•Use two complementary methods for signal extraction: b-tagging and kinematic LH
•4 (8) channels: e/μ+jets (including leptonic τ decays), 3/≥4 jets, (1/≥ 2 b-tags)

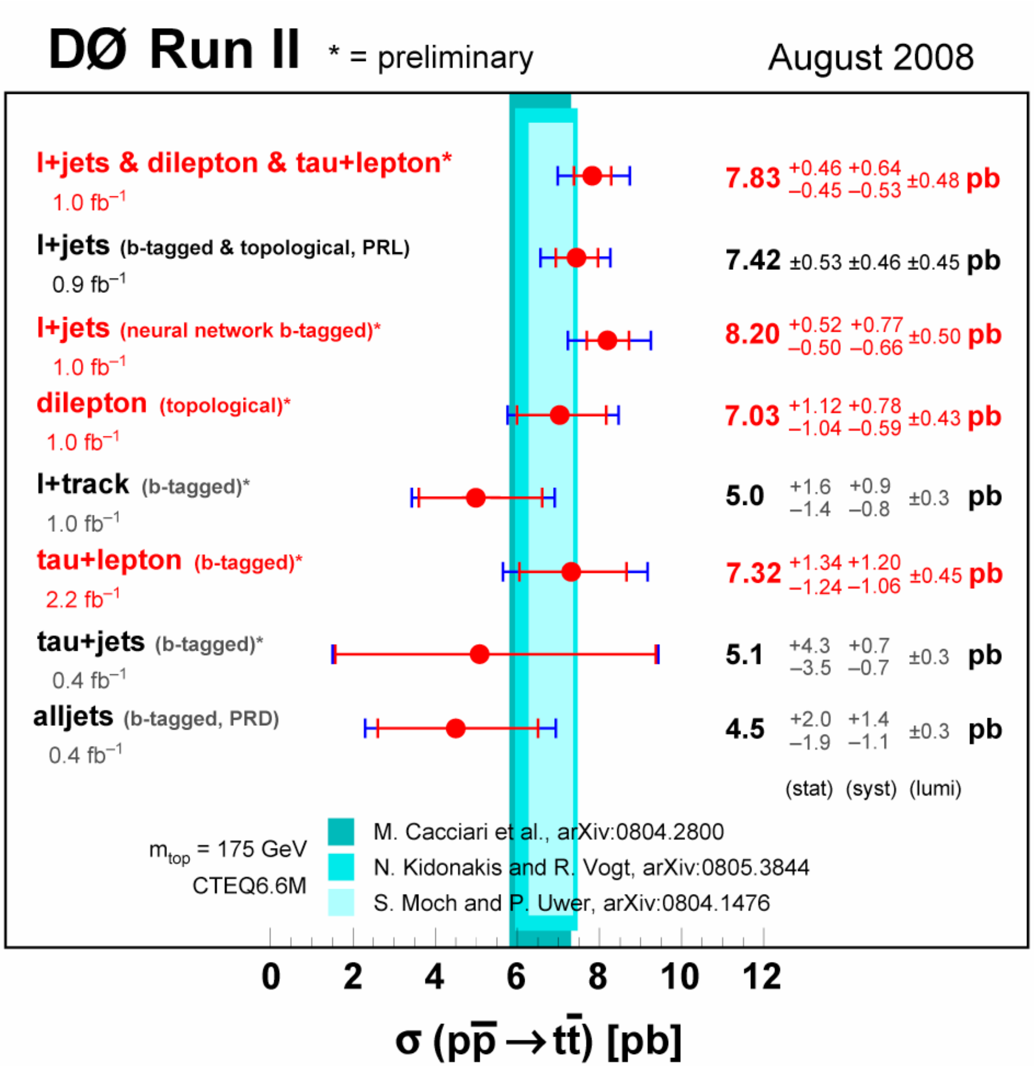


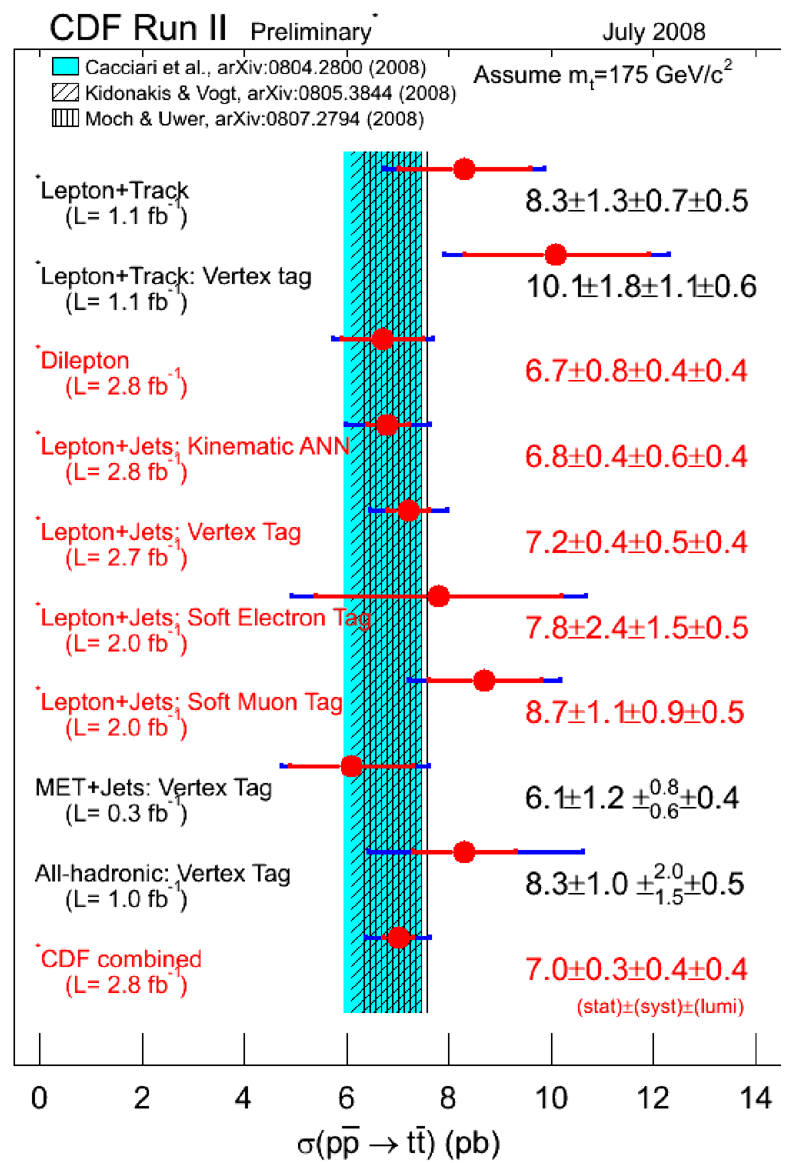


$$\boxed{\sigma_{tt} = 7.42 \pm 0.53 \text{ (stat)} \pm 0.46 \text{ (syst)} \pm 0.45 \text{ (lumi) pb}}$$

(m_t=175 GeV, PRL **100**, 192004, 2008)

Top Quark Pair Production: cross sections

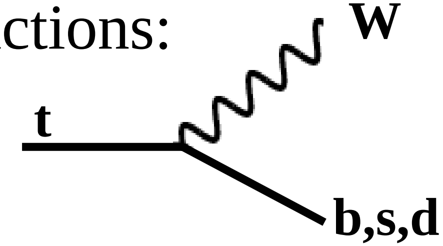


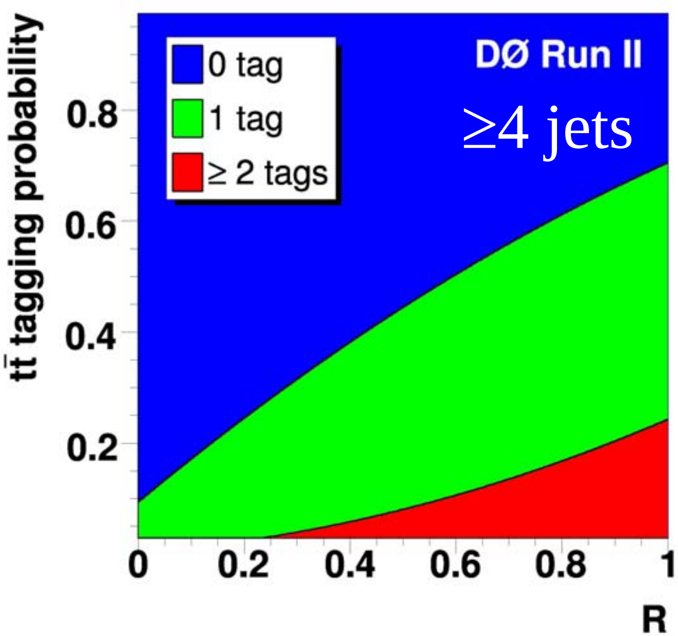


Simultaneous measurement of σ_{ttbar} and R

SM: top decay rate $\propto |V_{tq}|^2$ – study ratio of branching fractions:

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$





- Measure σ_{ttbar} and R simultaneously via tagging prob.
- No assumption of $B(t \to Wb) = 1$
- Higher precision on R,σ: different sensitivity to syst.

$R = 0.97^{+0.09}_{-0.08}\,(stat + syst)$ (PRL **100**, 192003, 2008)

$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}\,(stat + syst) \pm 0.50\,(lumi)\ pb$

0.9 fb^{-1} l+jets dataset   for m_t=175 GeV

$R > 0.79$ @ 95% C.L.

$|V_{tb}| > 0.89$ @ 95% C.L.

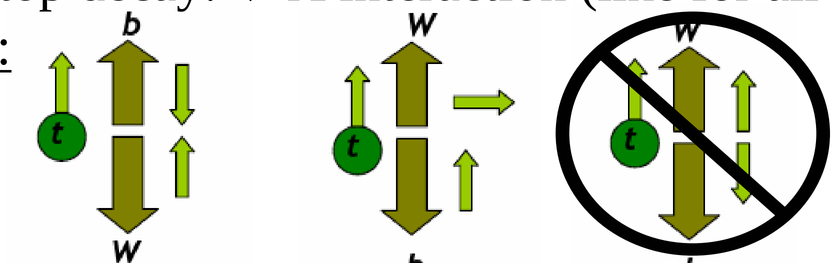
(3x3 unitary CKM matrix)

best limit to date!

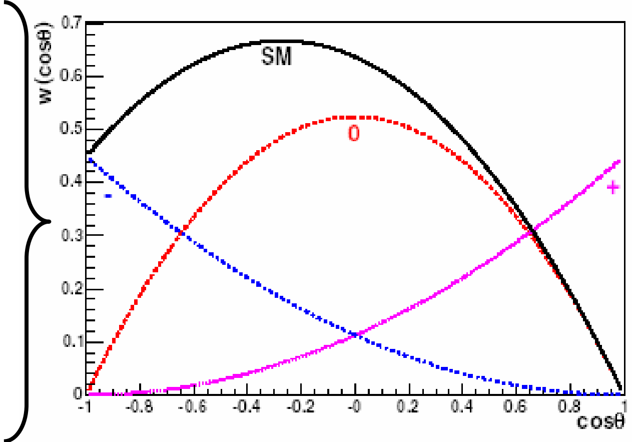
W Helicity in top decay

Standard Model top decay: V-A interaction (like for all fermions)

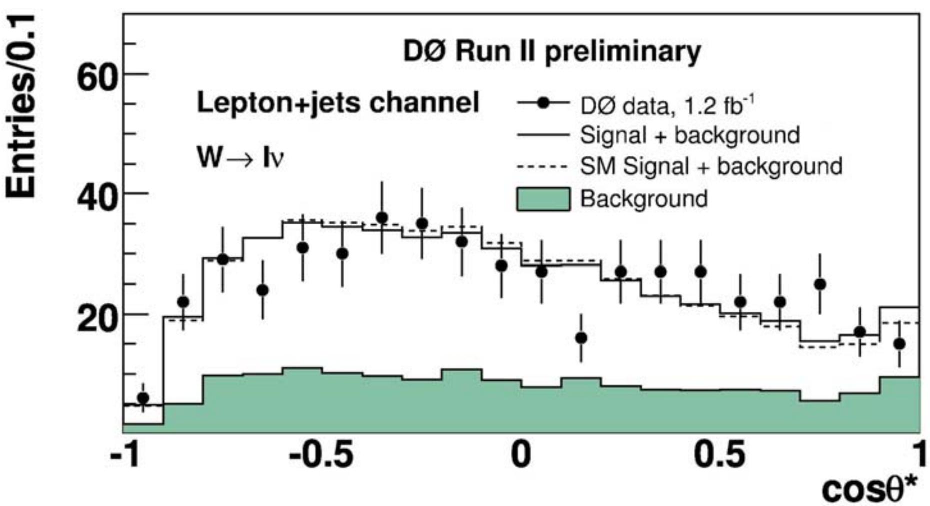
W helicity states:

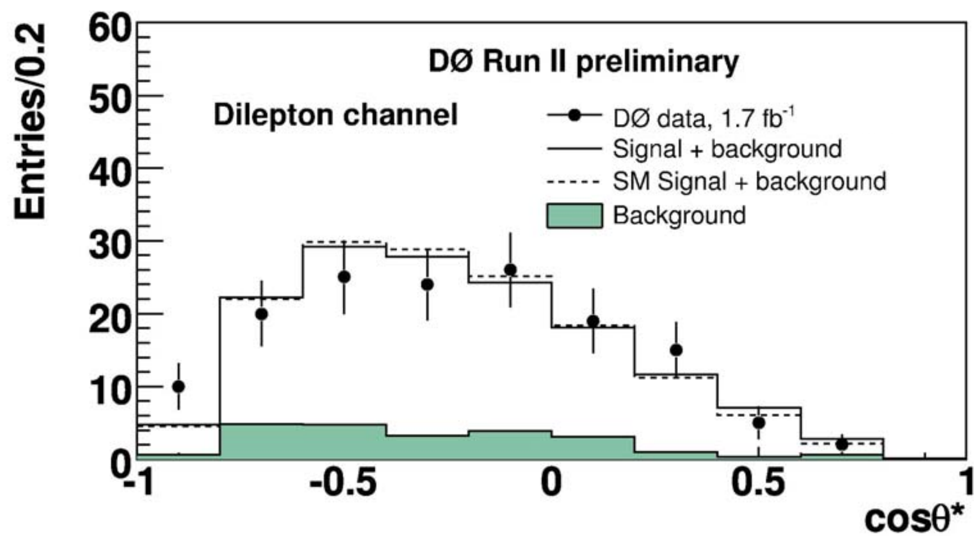


	left-handed fraction: f_-	longitudinal fraction: f_0	right-handed fraction: f_+
In Standard Model:	**~30%**	**~70%**	**~0.036%**

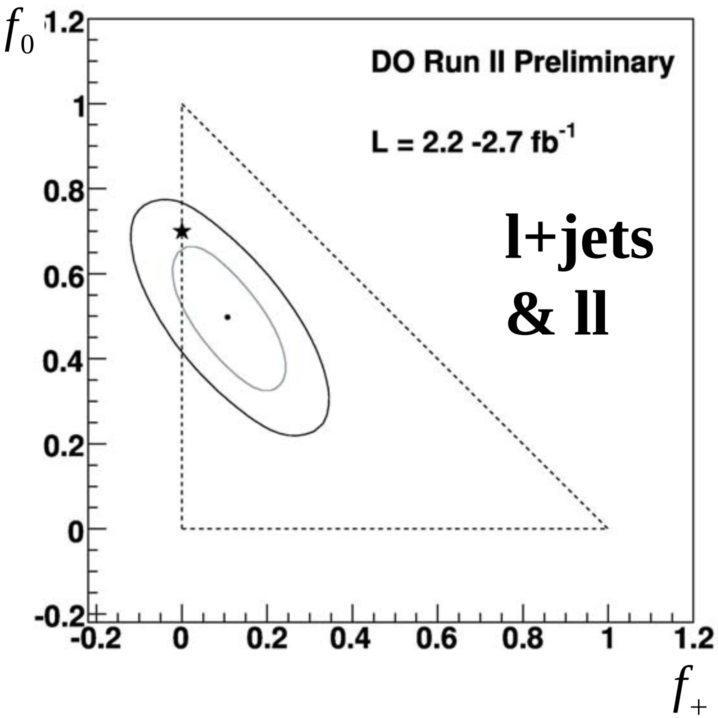


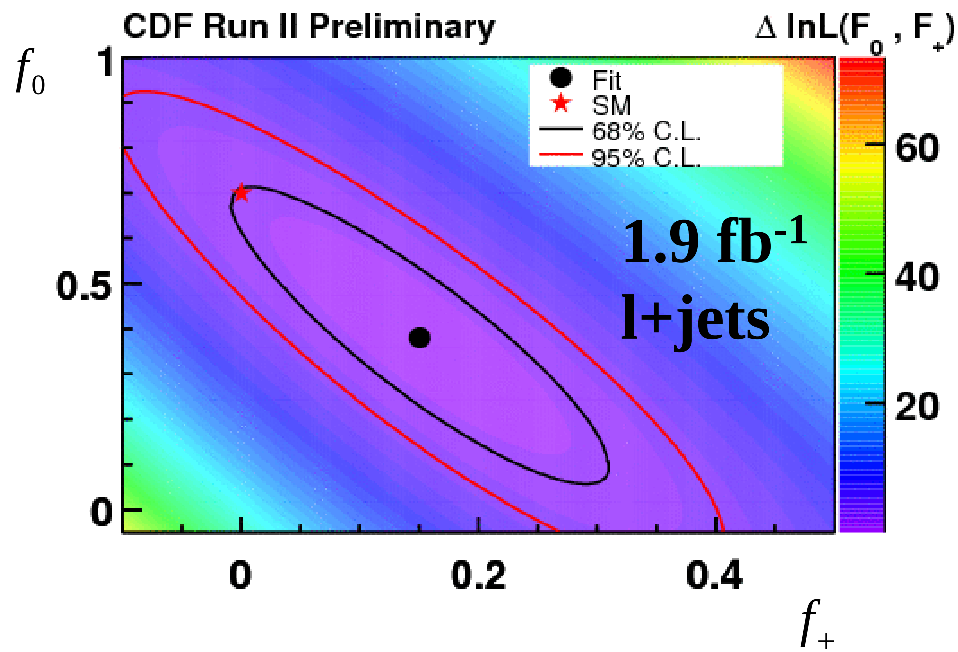
⇒ Measure angular distribution of charged lepton wrt. top in W rest frame: $\cos\theta^*$





W Helicity in top decay





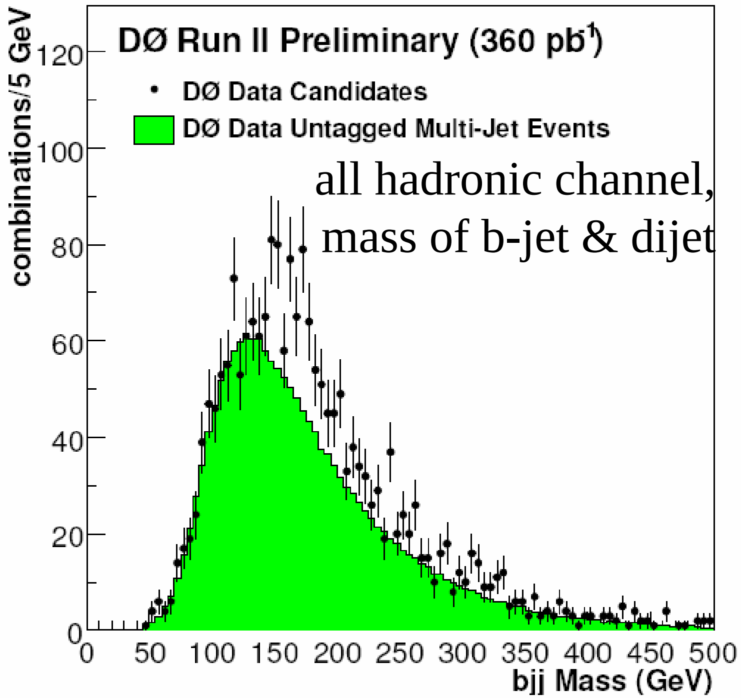
$f_0 = 0.49 \pm 0.11$ (stat.) ± 0.09 (syst.)
$f_+ = 0.11 \pm 0.06$ (stat.) ± 0.05 (syst.)

$f_0 = 0.38 \pm 0.21$(stat) ± 0.07(syst)
$f_+ = 0.15 \pm 0.10$(stat) ± 0.05(syst)

So far consistent with Standard Model expectation.

Top Quark Mass Measurements

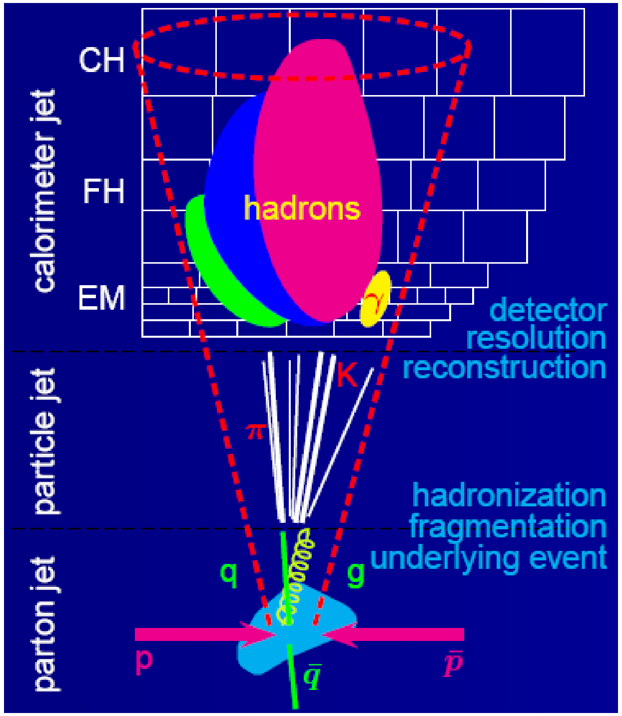
Many Methods exist - general features:
- Measure observable sensitive to Top mass
- Map partons to reconstructed objects (combinatorics!)
- Calibrate with pseudo-experiments
- Obtain mass via maximum likelihood



all hadronic channel, mass of b-jet & dijet

Need to relate the reconstructed calorimeter jets back to parton level:

Jet Energy Scale is crucial!



Top events: W boson decay products allow for additional **in-situ jet energy calibration**

Top Quark Mass Measurements: Matrix Element Method

- Matrix Element Method: yields so far most precise measurements
- Use four-vectors of reconstructed objects to calculate per event probability density for being signal/background as function of m_t
- Maximises use of information on the event, but CPU intense calculations
- Product of event probabilities allows to extract the most likely mass value:

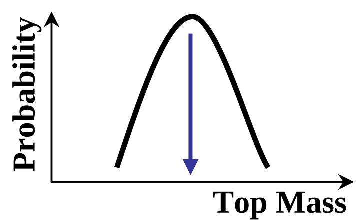
$$P_{t\bar{t}}(x, m_t, JES) = \underbrace{Acc(x)}_{\text{Acceptance}} \overbrace{\frac{1}{\sigma_{t\bar{t}}(m_t)}}^{\text{Normalisation}} \int \underbrace{dq_1 dq_2 f(q_1) f(q_2)}_{\text{initial state}} \overbrace{d\sigma(y, m_t)}^{\text{Partonic differential Cross Section, based on LO Matrix Element}} \underbrace{T(x, y, JES)}_{\text{Transfer Function: Prob. to measure x from parton-level y}}$$

use hadronic W decay

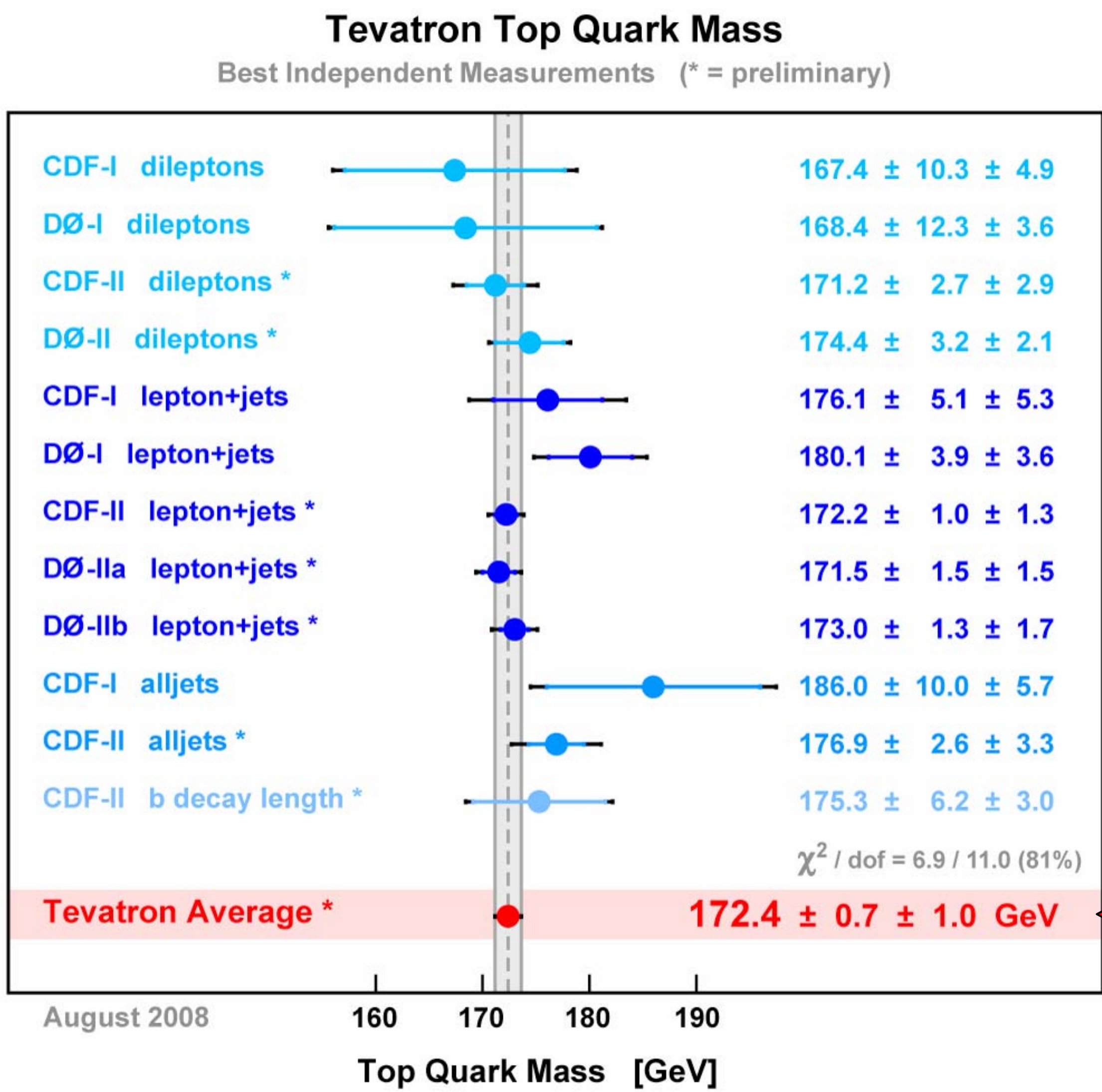
m_{top} =172.2 ± 1.0 (stat.) ± 1.4 (syst.) GeV

(2.2 fb^{-1}, lepton+jets channel)

=



Tevatron Top Quark Mass



Combination of Tevatron Top Quark mass measurements yields most precise quark mass:

<u>172.4 ± 1.2 GeV</u>

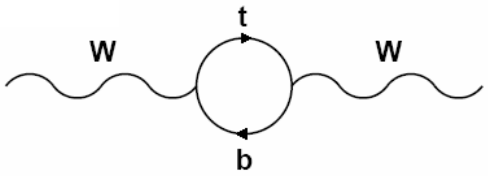
(August 2008)

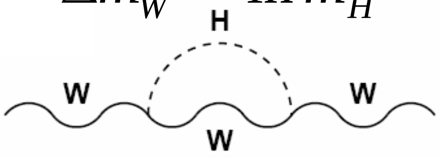
0.7 % Precision!

Goal: $\Delta m_t \leq 1$ GeV in Run II

Top Quark Mass and SM Higgs

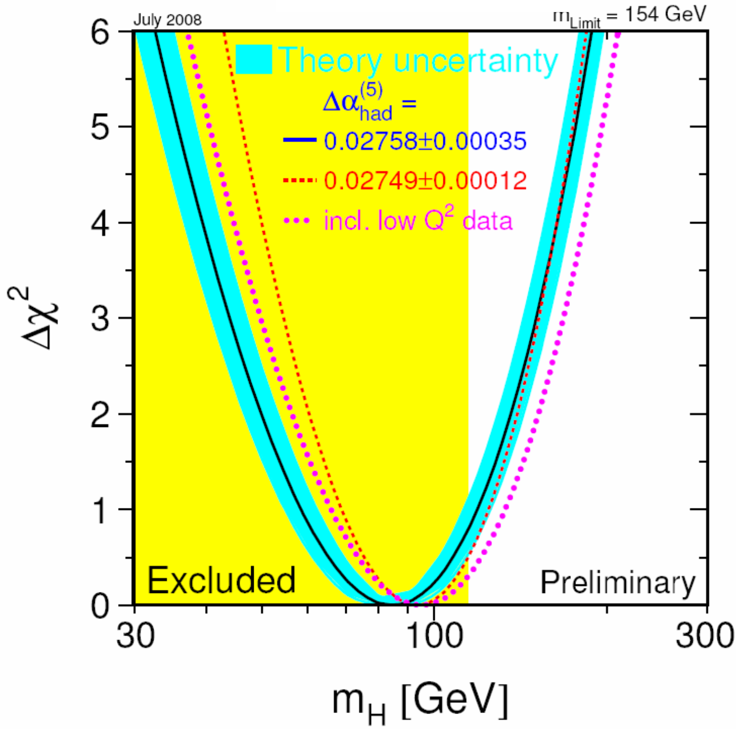
$\Delta m_W \propto m_t^2$ $\Delta m_W \propto \ln m_H^2$



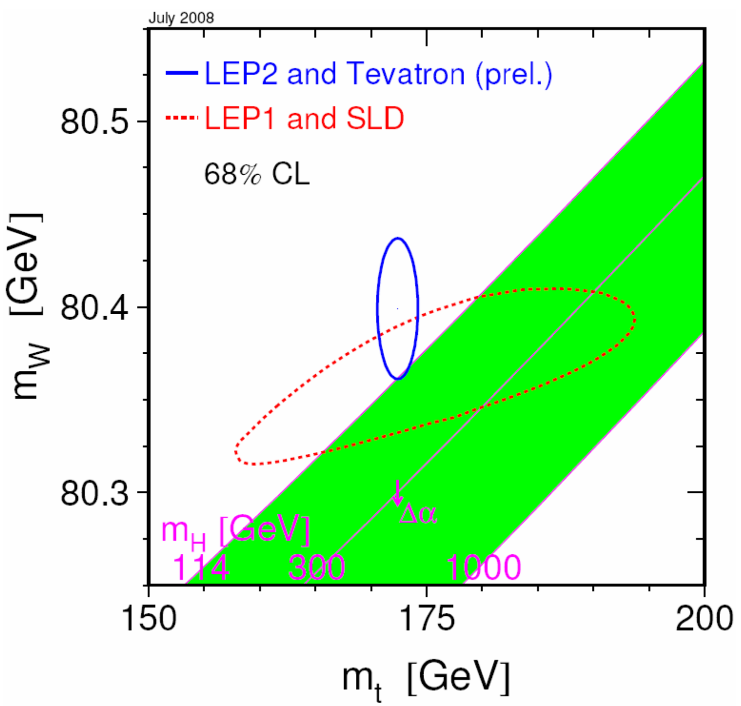


•radiative corrections on the W mass allow constraints on Higgs mass from m_W, m_t

Fall 2008



Fall 2008



preferred m_H : 84^{+34}_{-26} GeV

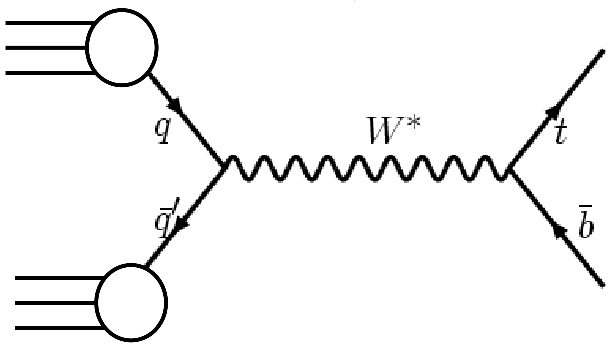
m_H < 154 GeV @ 95% C.L.

Single Top Quark Production

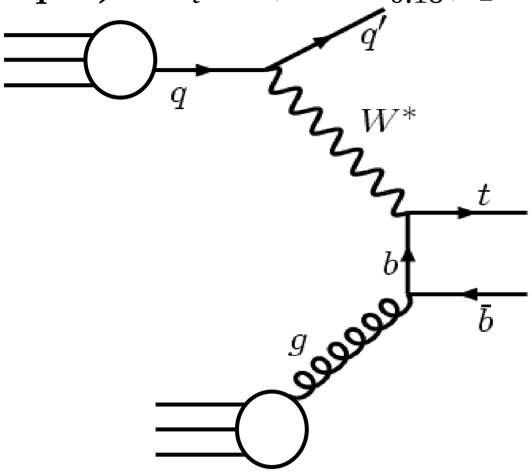
Single Top production (EW interaction):

(Theoretical expectation from
Z. Sullivan, PRD **70**, 114012 (2004),
m_t=175 GeV)

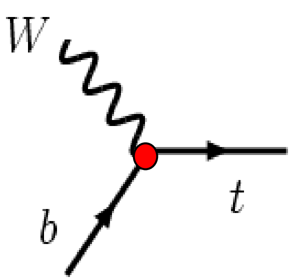
- s-channel ("tb"): $\sigma_s = (0.88^{+0.07}_{-0.06})$ pb



- t-channel ("tqb"): $\sigma_t = (1.98^{+0.23}_{-0.18})$ pb



Why measure this?

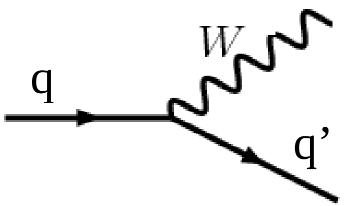


- $\sigma(tb, tqb) \propto |V_{tb}|^2$
- Test unitarity of CKM matrix
- Sensitive to new physics:
  Resonances? FCNC?

$$\begin{array}{cc} \begin{array}{c} u \rightarrow \\ c \rightarrow \\ t \rightarrow \end{array} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix} \\ & \begin{array}{ccc} \uparrow & \uparrow & \uparrow \\ d & s & b \end{array} \end{array}$$

The CKM Matrix

W.-M. Yao *et al.*, Journal of Physics G **33**, 1 (2006) :



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ux} \\ V_{cd} & V_{cs} & V_{cb} & V_{cx} \\ V_{td} & V_{ts} & \color{red}{V_{tb}} & V_{tx} \\ V_{yd} & V_{ys} & V_{yb} & V_{yx} \end{pmatrix} \quad ?$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.22[illegible]^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & \text{no direct measurement} \end{pmatrix},$$

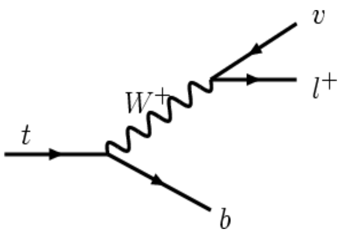
What do we know about V_{tb}? Within Standard Model framework:

- 3 generations
- unitarity of CKM matrix

$$\left.\begin{array}{l} \text{3 generations} \\ \text{unitarity of CKM matrix} \end{array}\right\} V_{tb} = 0.999100^{+0.000034}_{-0.000004}$$

More than 3 generations ($V_{td}^2 + V_{ts}^2 + V_{tb}^2 < 1$)**: 0.07 <$V_{tb}$<0.993 (90% CL)**
Direct measurement only via single Top production!

Single Top selection



signature: similar to $t\bar{t}$ l+jets, but lower jet-multiplicity ⇒ **b-tagging**!
background: W+jets, $t\bar{t}$, $b\bar{b}$, multijets faking leptons
⇒ **Look at 12 analysis channels**: e/μ, 1/2 tags, 2/3/4 jets

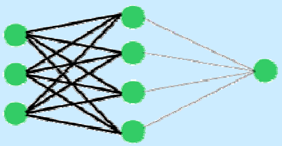
Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined		
	2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

Single Top signal is smaller than total background uncertainty!

Cut & count events
not sensitive enough!
(S:B from 1:10 to 1:40)

Use multivariate discriminants to separate signal/background:

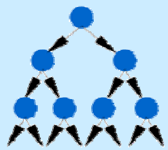
Single Top analysis methods



Bayesian Neural Networks
Trained, discriminating variables

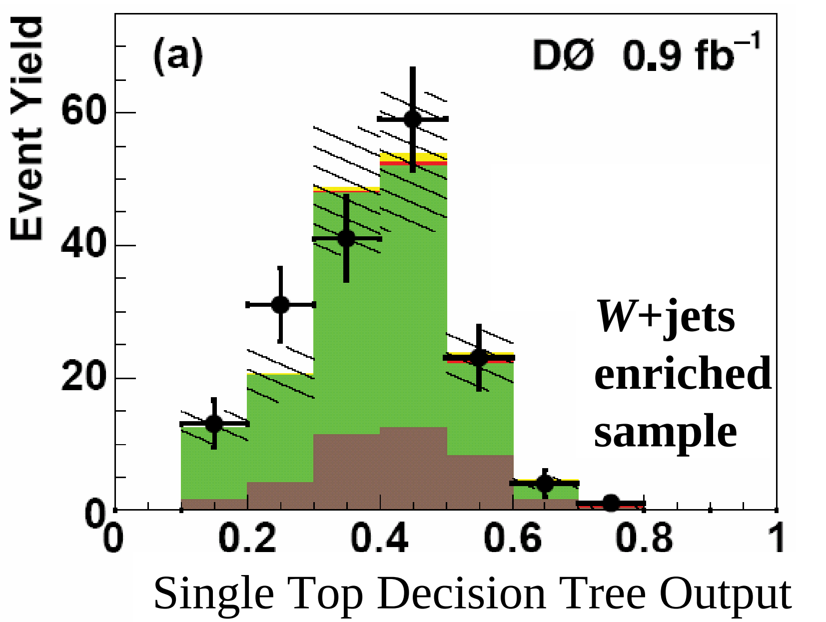
$\int M$

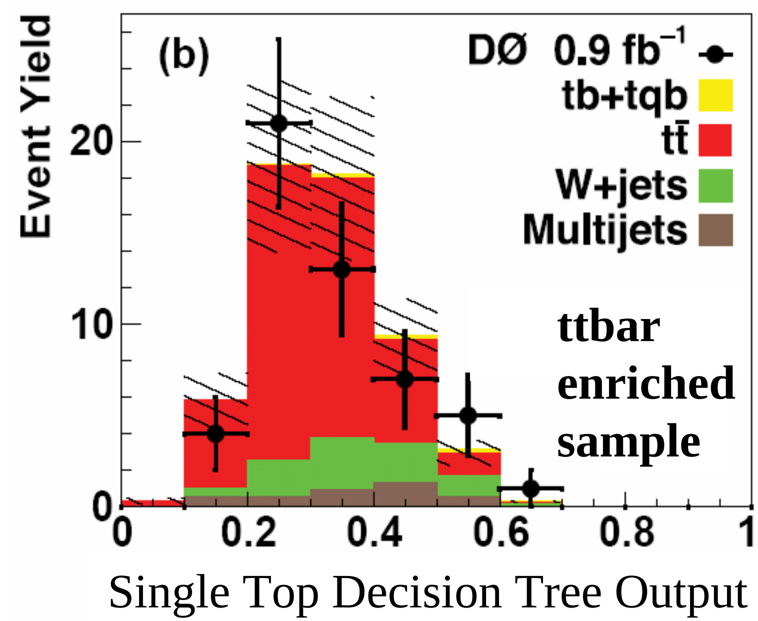
Matrix Element: 4 vectors and
MC LO matrix elements



Boosted Decision Trees
Trained, discriminating variables

Make sure that backgrounds are well modelled: low discriminant region, signal depleted (cuts)

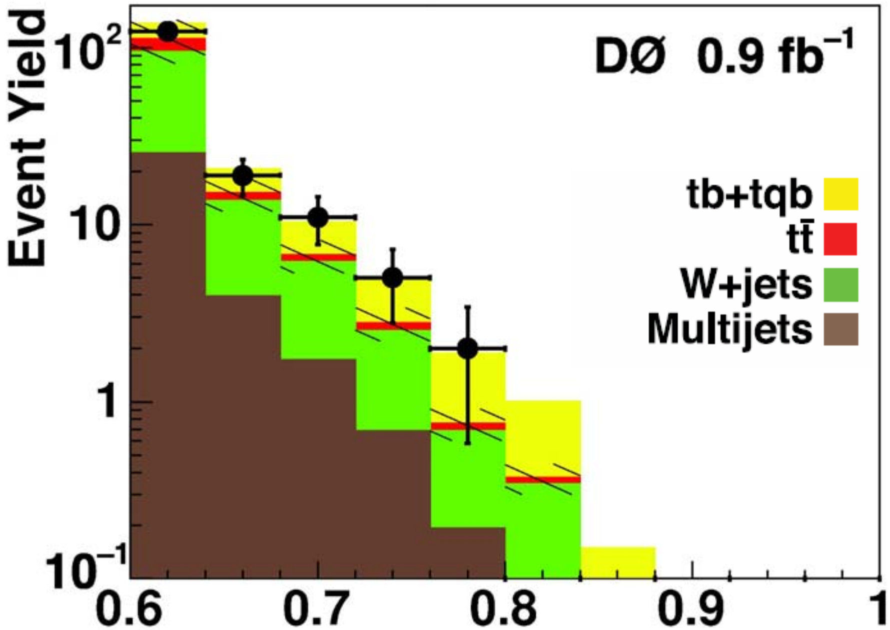




Make sure machinery is well understood and calibrated: ensemble tests

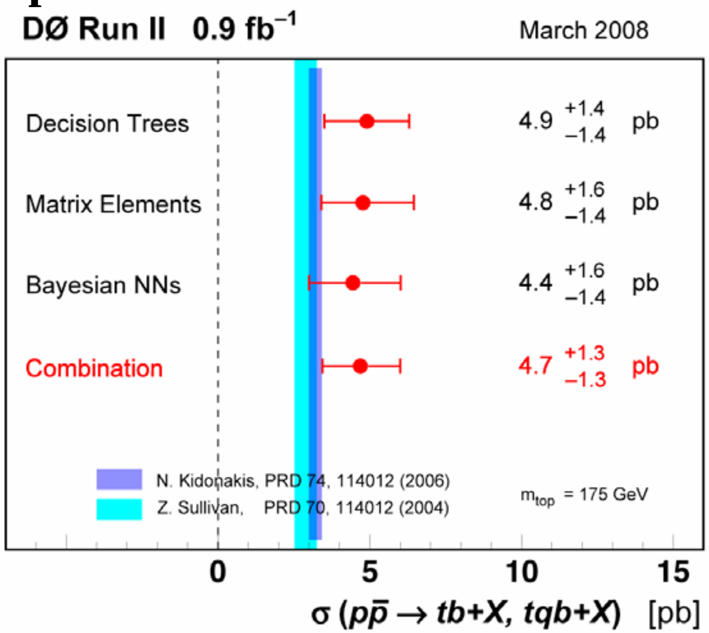
Single Top cross section results

Decision Tree result (most significant) :



Single Top Decision Tree Output

comparison & combination of methods:



$\boldsymbol{\sigma(tb+tqb) = 4.9 \pm 1.4}$ **pb**

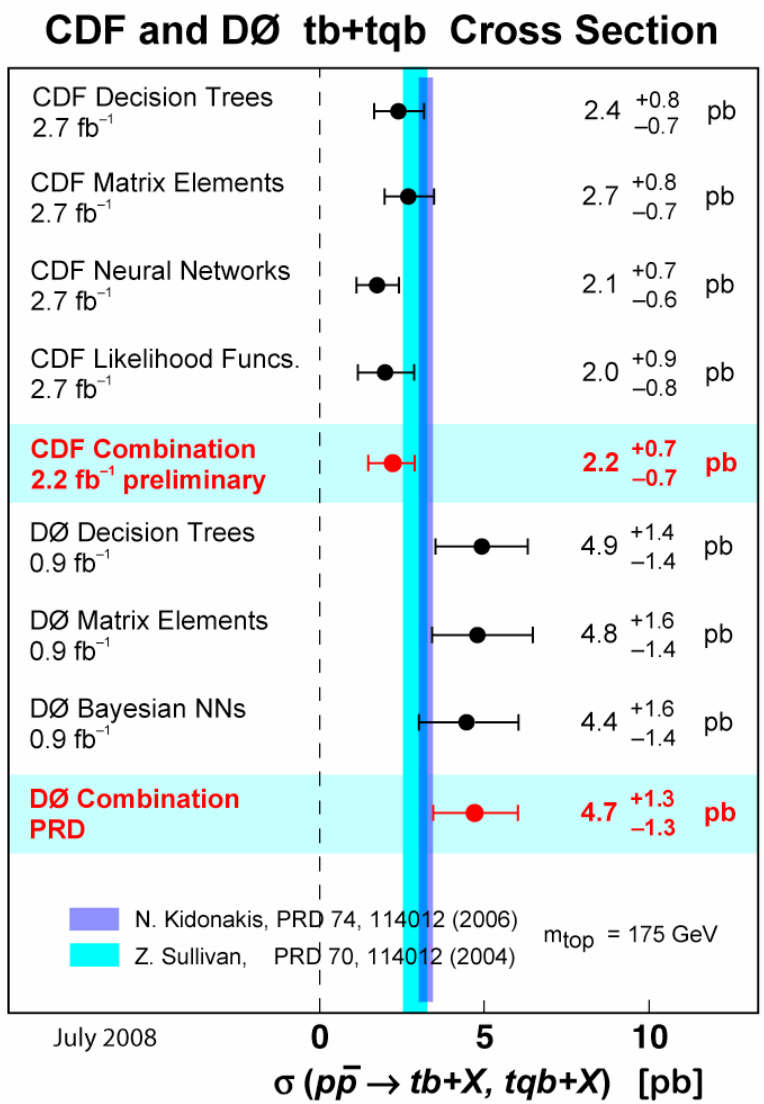
significance = 3.4 σ

Compatibility with SM xsec = 11%

First Evidence for Single Top Quark Production

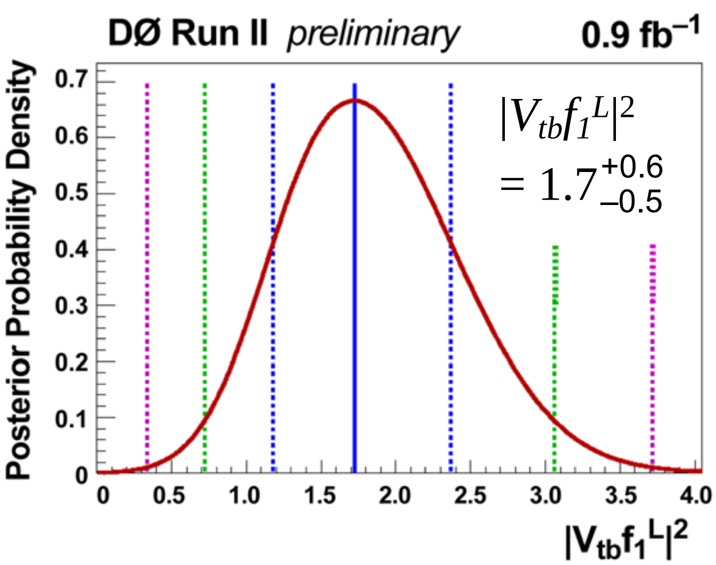
PRL **98,** 181802 (2007)
PRD **78**, 012005 (2008)

Single Top cross section results



$|V_{tb}|$ measurement

Using Decision Tree result, assuming:
- $V_{td}^2 + V_{ts}^2 << V_{tb}^2$ and
- pure V−A and CP-conserving Wtb interaction, anomalous strength allowed



$|V_{tb}\, f_1^L| = 1.3 \pm 0.2$

$0.68 < |V_{tb}| \leq 1$ at 95% C.L.

(assuming V-A coupling strength $f_1^L = 1$)

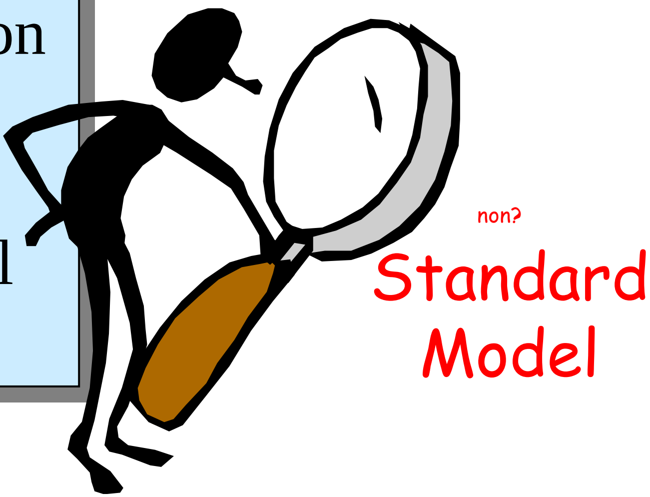
Latest CDF ME analysis (2.7 fb^{-1}):

$|V_{tb}| > 0.71$

No assumption needed on the number of fermion families or the unitarity of the CKM matrix for the first time!

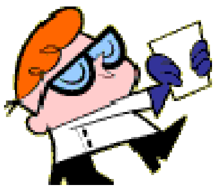
Summary

- Entered era of precision measurements:
  mass, cross-section – understand systematics!
- Still lots to learn about the Top Quark – some properties just become measurable @ Tevatron
- Impressive progress in analysis techniques
- Top is ideal probe for "New Physics"
- **So far:** good agreement with Standard Model
- There's still plenty room for surprises…

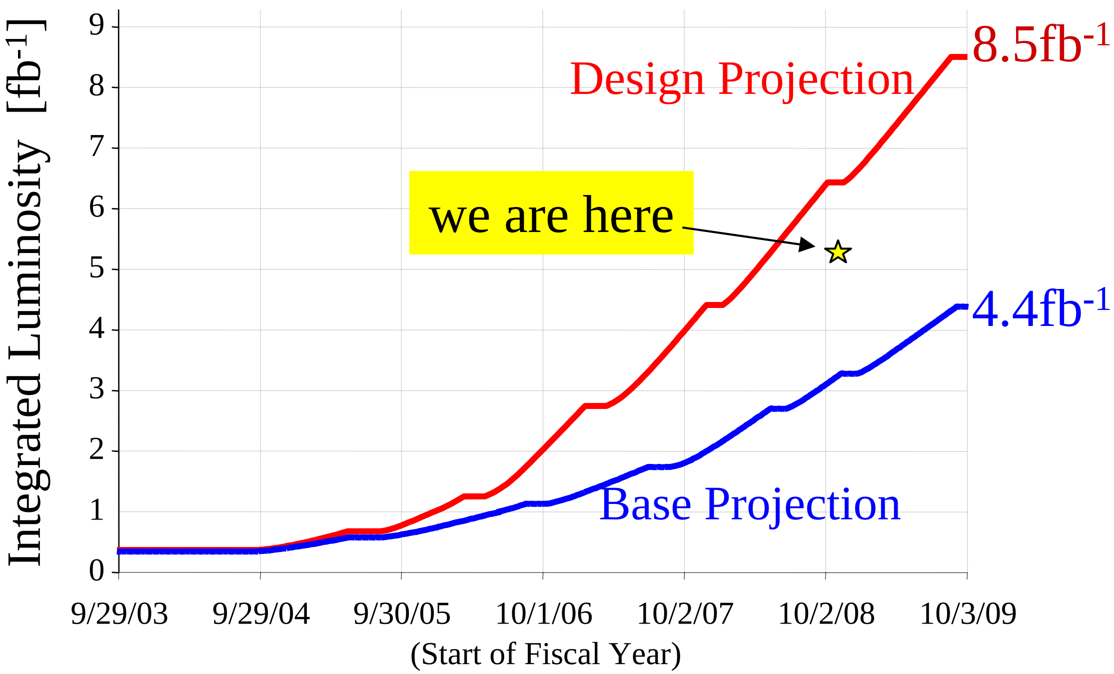


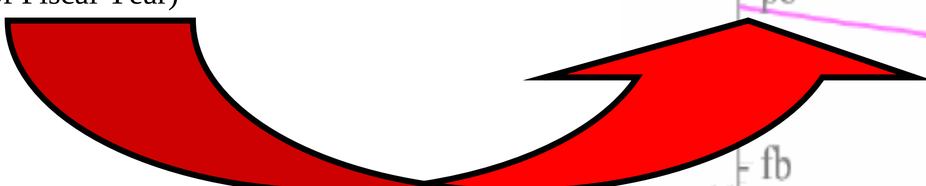
More measurements / information available online:

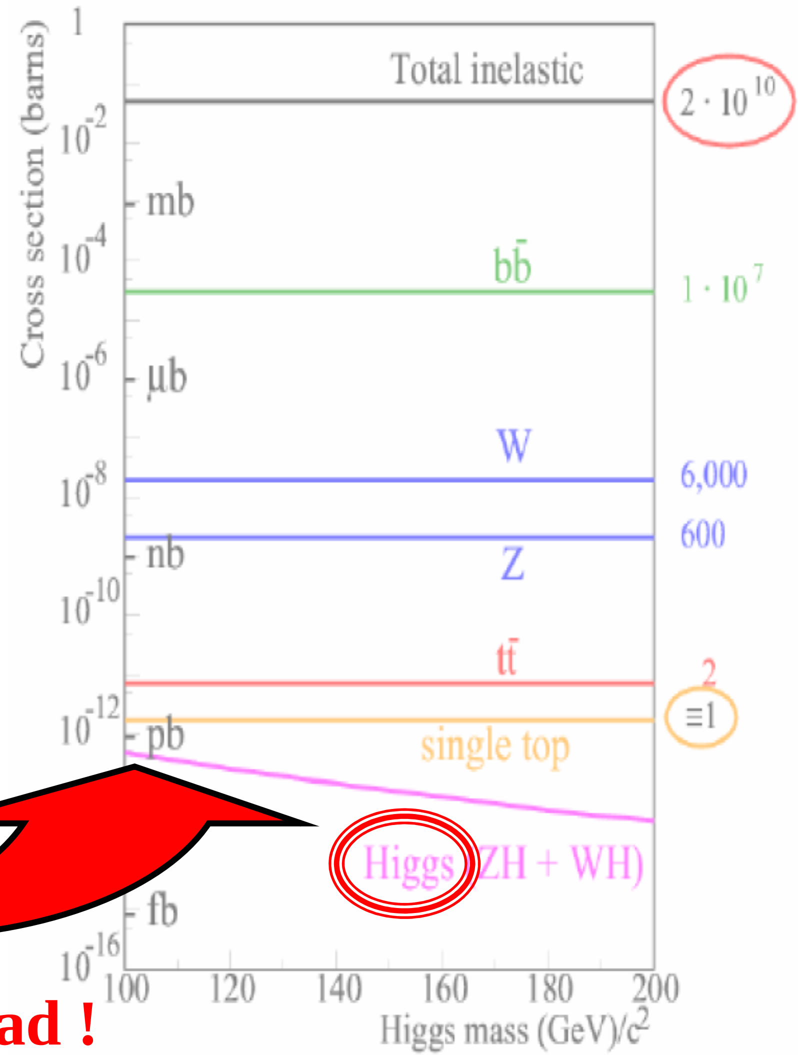
- M.-A. Pleier, arXiv:0810.5226v1
  "Review of Top Quark Properties Measurements at the Tevatron"
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://www-cdf.fnal.gov/physics/new/top/top.html



Outlook







More exciting results ahead !